G.E.C. Journal

VOL. XIX JULY, 1952 No. 3

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Published by

THE GENERAL ELECTRIC COMPANY LIMITED
Magnet House, Kingsway, London, England.

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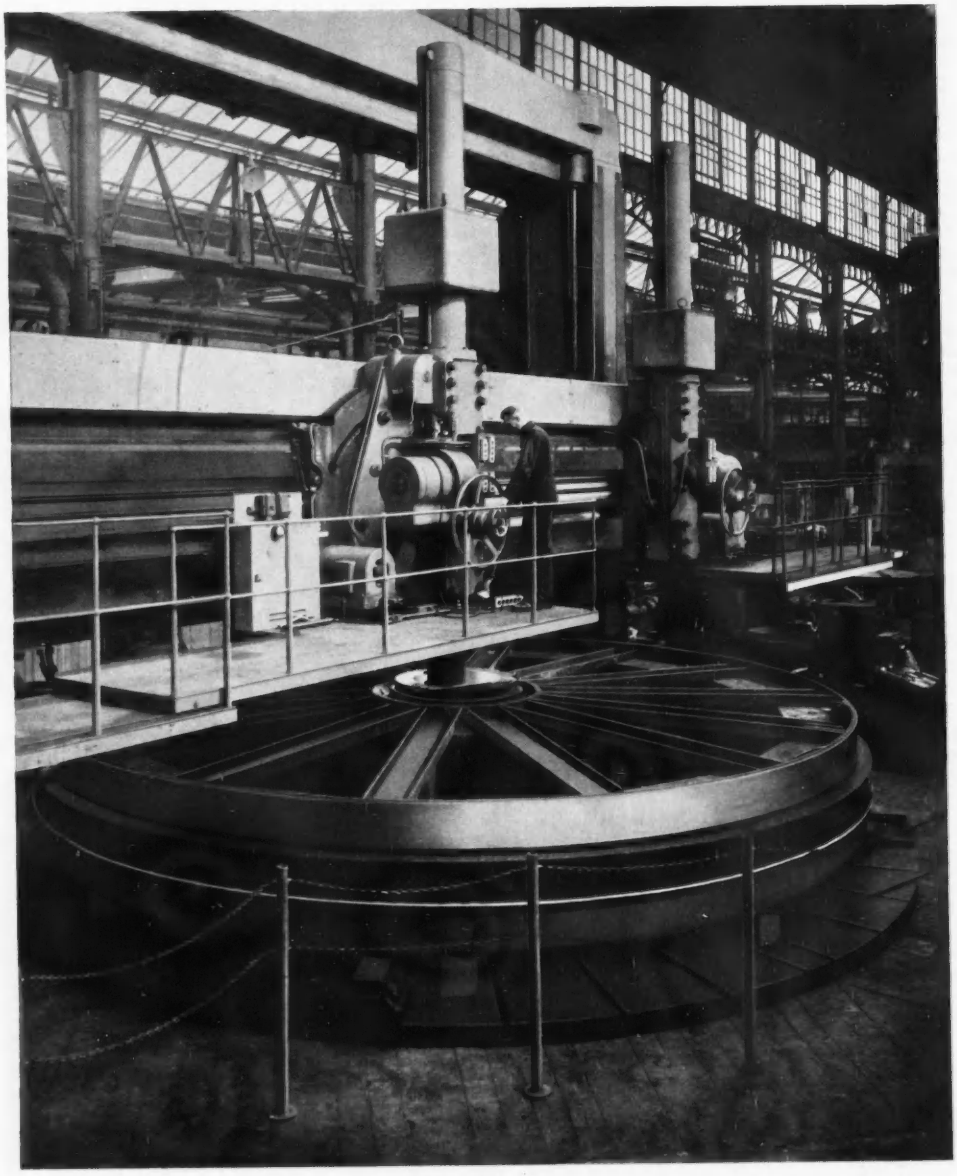


KOEPE WINDER.

A 24 ft. Koepe wheel for Bradford Colliery being machined at Fraser & Chalmers Engineering Works. Entirely of welded construction, it is one of the largest wheels of this type manufactured in this country.

Mobile and Permanent Rectifier Substations for the Netherlands Railways

By Ir. B. P. VEREL, The Hague, and
W. G. THOMPSON, Ph.D., M.I.E.E., G.E.C. Rectifier Works, Witton.

INTRODUCTION.

THERE can be few, if any, mercury arc rectifier installations of greater historical or economical interest than those of the Netherlands Railways. The historic interest lies, first, in the loss of practically all the electrical equipment during the heroic strike carried out by the Railways in September, 1944, when under orders from the Dutch Government in London they ceased work to prevent supplies reaching the occupying German Forces. Second, there were the vigorous and effective measures taken by the Netherlands Railways to rehabilitate their systems which had been methodically pillaged by the Germans in retaliation for the strikes. The economic significance of the installations lies in the fact that the Netherlands Railways have embarked on an extensive programme of electrification, after examining alternatives such as diesel-electric traction, because they have established that it is only by complete electrification that they can effectively compete with road transport in a small country like Holland. In this connection the widespread adoption of the pumpless steel tank rectifier as representing the most economic converting plant should be noted.

The story of the rehabilitation of the rectifier network, substations and rolling stock has been graphically described in a paper by Mr. van Lessen, formerly Chief Engineer of the Netherlands Railways, at the Institution of Electrical Engineers in 1949 and this article records some of the developments which have taken place since that date, under the direction of the Chief Electrical Engineer, Mr. Ir. E. van der Hoek, assisted, first, by Mr. P. J. Koster, and up to the present date by Mr. Ir. J. E. J. Ankersmit.

The problem of bringing the railways once more to the desired performance as a transport system was essentially twofold, the arrangements for extending the electrified line proceeding hand in hand with the restoration of the lines electrified before the war. It followed that not only was a considerable amount of new plant required, but that the rectifier equipment, with which this article is mainly concerned, had to be suitable for operating as an integral part of a substation containing existing gear, or if the substation supplied was completely new it had to be capable of working in parallel with existing rectifier substations.

NETHERLANDS RAILWAYS NETWORK.

These technical requirements have to be visualised against the background of the geographical layout of the railways system and fig. 1 shows the main features of the Netherlands Railways network. It will be seen that the main groups of electrified lines spread out fan-wise in a westerly direction from Utrecht. Completion of the lines to the westward was carried out before the war and included the densely populated area around the Amsterdam and Rotterdam districts and extending up the coast northwards to Alkmaar, the whole forming a triangle bounded on two sides by the North Sea and Zuider Zee, respectively, with a base line roughly from Utrecht to the Hook of Holland.

From Utrecht there were also two main electrified lines, one in a southerly direction to Eindhoven, and one running East to Arnhem and Nijmegen. In 1949, the line to Eindhoven was extended into Limburg, the coal mining district. The electrification of the second main eastern line (from Amersfoort via Deventer to Enschede) took place in 1950-51 and north of this area two other lines have been electrified. These are the lines Amersfoort-Zwolle-Leeuwarden and Amersfoort-Zwolle-Groningen,

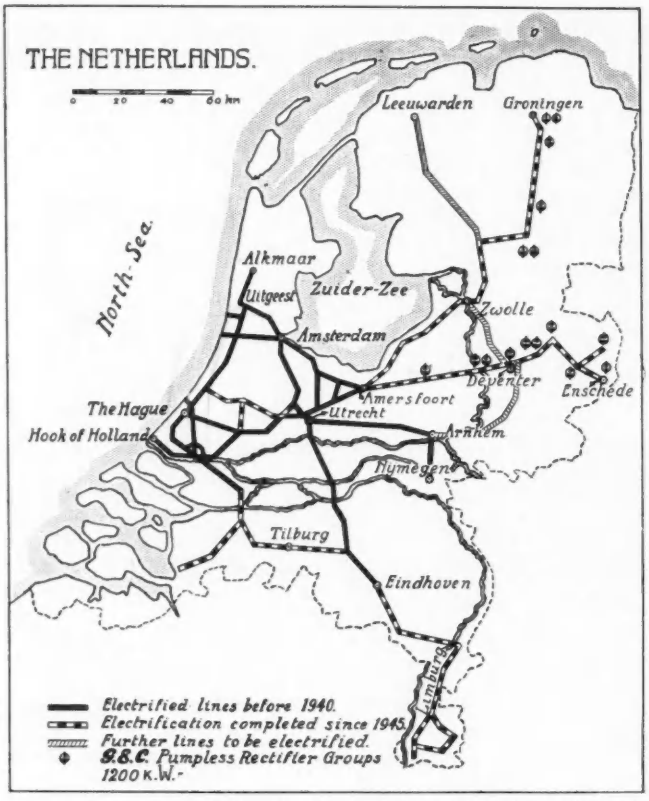


Fig. 1.—Map of Holland showing the electrified lines of the Netherlands Railways and the location of the pumpless rectifier equipment.

which have both been put into commission as electrified lines on the 1st May, 1952.

The Dutch engineers had begun to electrify their railways in 1921, using 1,500 volts D.C. carried on overhead conductors (fig. 2). After the 1939 war they examined the suitability of 3,000 volt D.C. electrification, but came to the conclusion that 1,500 volts was still the most appropriate voltage for their new extensions.

POWER SUPPLIES.

The main E.H.T. transmission system in Holland is at 150 kV, 3 phase, 50 cycles. In addition to the generating stations in Holland itself, there are transmission lines running through into Germany and the interconnection is such that it is possible for Holland to import power or export power to such countries as Switzerland dependent upon respective availability of coal or water power. For purposes of supplying the railways the power is transformed down to 10 or 25 kV. The transformers are connected mostly in star/star in South Holland, while in the area northwest of Amsterdam delta/star connection is also common. The 1,500 volt rectifier substations are supplied at 10 kV or 25 kV and are spaced roughly at 6-mile intervals along the track.

CONDITIONS GOVERNING THE CHOICE OF SUBSTATIONS.

The substations installed before the war were designed with ample spare rectifier capacity as a safeguard against breakdowns. The rectifying units employed in these substations comprised one water-cooled rectifier with each transformer, but the introduction of the air-cooled pumpless rectifier with its absence of vulnerable auxiliaries made it possible to decrease the spare plant capacity in the substations. Furthermore, the simplicity of this type of rectifier makes it eminently suitable for unattended substations, and one of the first steps after the war was to order a number of these.

An order for the first two mobile rectifier substations (fig. 3) was placed with the G.E.C. in 1945 followed by a repeat order for two similar substations in 1949. Concurrently with these, the Company was entrusted with an order for sixteen permanent substations in 1947 to be located on the various electrified portions of the railway as shown in fig. 1. A repeat order for two permanent substations has also been received, bringing the total of rectifiers supplied, or being built, by the G.E.C. for the Netherlands Railways to over 26,400 kW.

The mobile equipments are directed to substations where rehabilitation calls for spare rectifier capacity or where the load is temporarily in excess of the capacity of the permanent substations. Incidentally, a feature of the Netherlands Railways' permanent substations is the provision of a short length of siding on to which a mobile rectifier can be run in order to back up

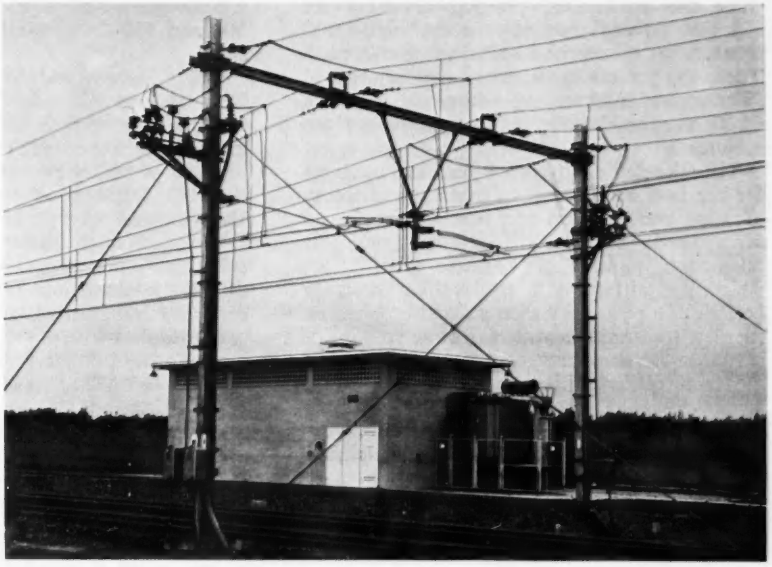


Fig. 2.—The 1,500 volt overhead conductor system at Kootwyk, with a typical substation in the background.

the supply from a permanent substation. This means that the characteristics of the two types of substation must tally.

The operational characteristics of both types of substation were determined largely by those of the existing equipments with which they were required to work in parallel. For example, the Dutch engineers favoured a very slight droop in the voltage load characteristic of less than 4 per cent at a load of 1,800 kW on the substation. This low regulation had been adopted for the pre-war substations which had each been equipped with a 1,200 kW water-cooled 6-phase rectifier, supplied by an 1,800 kW rectifier transformer. The transformers were 6-phase with double windings on their secondary sides

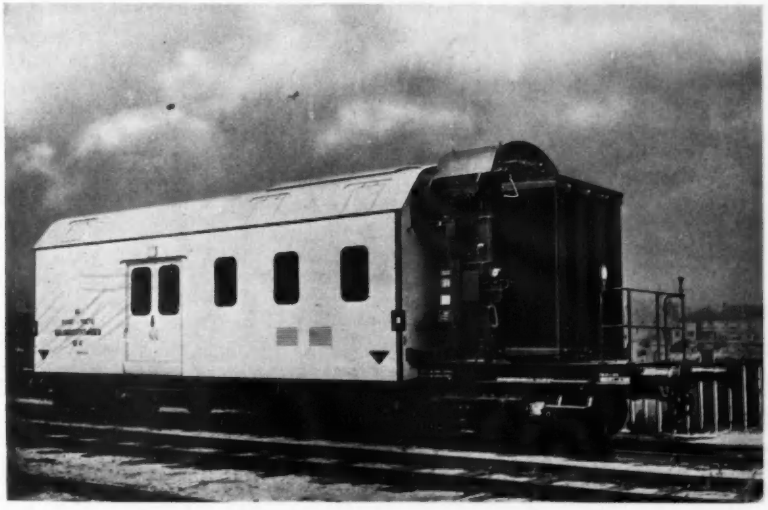


Fig. 3.—1,224 kW, 1,530 volt mobile substation in service on the Netherlands Railways.

while the continental practice of using arc suppression and reverse current high-speed breakers for the rectifier had also been adopted. These equipments had overload requirements of 150 per cent load for two hours with peaks of 4,000 amperes lasting ten seconds every ten minutes.

The adoption of air-cooled pumpless rectifiers for the new installations offered the possibility of using two rectifiers per transformer instead of a single water-cooled rectifier and this raised the question of 12-phase rectification, which was attractive to the rectifier designer because the possibility then existed of building the new transformers with twice the amount of reactance for the same regulation, thus halving the fault current. British engineers tend to favour this, partly because it enables a simple form of rectifier equipment to be produced, by avoiding the need for arc suppression requiring control grids in the rectifier, and partly because it offers the possibility of eliminating the 5th and 7th harmonics in the circuit upon the supply side of the rectifier and eliminates the 300 and 600 cycle voltage ripple on the D.C. side.

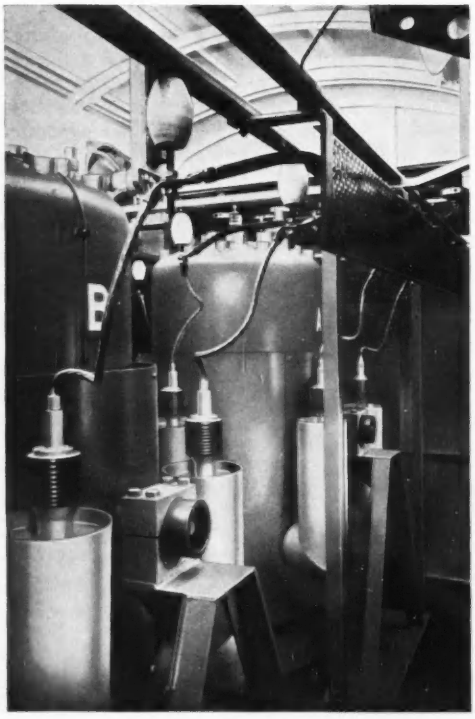


Fig. 4.—Interior view of mobile substation showing resilient mounting of pumpless rectifiers.

Offers were made to supply 12-phase for both the mobile and the permanent substations, but before the final decision was reached the Dutch engineers announced that a number of the original 6-phase double secondary transformers had been recovered from the Germans and they preferred to use these again at their permanent substations. This led to the compromise that 12-phase should be adopted on the mobile substations for reasons of simplicity and maximum reliability, and 6-phase, using twin cylinders with arc suppression, in the fixed substations; pumpless air-cooled steel tank rectifiers being used for both types of substation.

This decision still meant that a 12-phase rectifier equipment would be called upon to operate alongside 6-phase units on the same A.C. network and supplying a common D.C. load, but with the difference that the preponderance of 6-phase rectification was to be far greater than originally envisaged. This gave rise to some interesting technical considerations about the parallel operation of 6-phase and 12-phase rectifiers in close proximity, and, to anticipate information given in detail later, both types of rectifiers functioned perfectly in parallel and provided large scale verification of the theory of rectifier operation under these conditions.

MOBILE SUBSTATIONS.

Specification of Equipment.

Each mobile equipment is rated at 1,224 kW, 800 amps., 1,530 volts D.C. with overloads of 150 per cent load for 2 hours and 500 per cent load for 15 seconds following 6 hours on full load. The voltage regulation between no load and full load was 2·7 per cent, this being obtained by designing the transformer for 1,800 kW, as already mentioned. This is an interesting reversal of the policies adopted on some other traction systems where the transformer is deliberately designed to have a lower nominal output on the grounds that the rectifier cylinders have a high overload capacity for a short time, whereas the transformers have a considerable thermal capacity and need to be designed only on the basis of the r.m.s. rating of the whole substation taken over several hours. Also there are advocates of the policy of having a fairly steep regulation curve for traction rectifiers to improve the load sharing between adjacent substations and to provide a high reactance to limit possible fault currents. That the pumpless rectifier has fulfilled the more unusual requirements of the Netherlands Railways for their particular traction

conditions indicates the confidence which can be placed in this class of equipment.

Design of Equipment.

The rectifier cylinders themselves are of the air-cooled steel tank pumpless type embodying the G.E.C. vitric seal for supporting the anodes in the usual side arm construction. The ignition system for the cylinder is of the standard floating cup type in which the cup is drawn below the surface of the mercury to break a circuit and cause an arc to be drawn from a fixed rod supported axially within the rectifier. The usual auxiliary anodes are provided in stub arms to maintain the cathode spot under no-load conditions. The resilient mounting of the rectifier (fig. 4) is by channel iron triangular frames integral with the plinth for each rectifier, the plinth forming an air chamber into which air is blown by a multivane fan, the air passing from this chamber over the rectifier.

The 12-phase transformer supplying the rectifiers is of the oil-immersed naturally cooled outdoor type designed for an incoming voltage of 10 kV, 3 phase, 50 cycles and arranged with primary tappings at $\pm$ 2 per cent and $\pm$ 4 per cent for voltage adjustment. It is arranged with detachable radiators on one side and with a conservator on top.

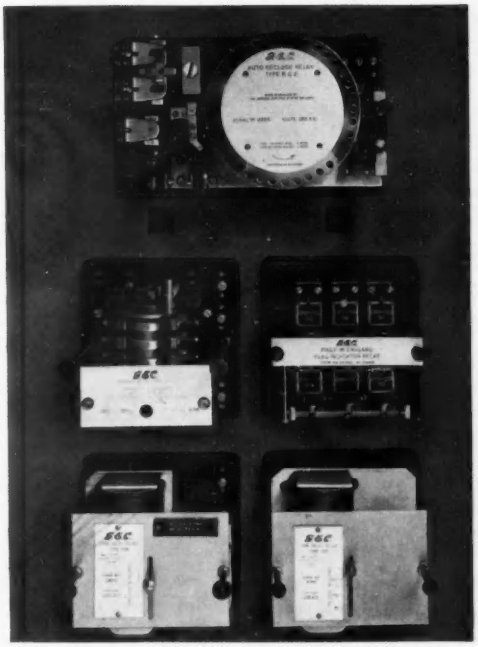


Fig. 5.—View of control panel in a mobile substation showing the auto-reclose lockout, flag indicator, sequence trip and a time delay relay.

The secondary winding is of the usual type, the 12-phase operation being produced by the interphase transformer method. A tertiary winding is also incorporated to supply the rectifier and other auxiliaries. Buchholz protection is also provided.

The control of the equipment on the incoming side is by means of a metalclad air-insulated oil switch unit with vertical isolation embodying a 400 amp. triple-pole solenoid-operated oil circuit breaker of 250 MVA breaking capacity fitted with two quick acting overload trips. An overload relay with fixed time lag, set at a lower value, is also fitted.

The D.C. switchgear consists of a 2,000 amp. single-pole air-break high-speed circuit breaker, floor mounted, electrically operated and arranged for high-speed reverse current tripping. The control gear is designed for remote operation so that the substation can operate unattended. An auto-reclose relay (fig. 5) is operated by the incoming " on " signal, and closes the oil circuit breaker, after which ignition, excitation and closing of the high-speed circuit breaker follow automatically. If, for some reason, the high-speed circuit breaker does not close, the relay repeats this operation up to three times with 15-second intervals before finally locking out the station. The lockout relay can only be reset by hand on site.

Lockout similarly occurs in the event of one of the following faults: cooling fan motor failure, Buchholz relay operation, excessive transformer temperature, earth leakage.

In case of any faults occurring such as reverse current, A.C. overload or excitation failure, the breakers are tripped and the auto-reclose relay is put into operation and restarts the station.

Tests at Works.

The equipment for each mobile rectifier substation comprising the A.C. switchgear, the transformer, rectifier, D.C. switchgear and all auxiliaries was manufactured and tested at the Witton Works of the G.E.C., shipped over to Holland and re-erected on a standard vehicle of the Netherlands Railways.

The combined equipment was subjected to load runs and short circuit tests at the Works.

ARRANGEMENT OF EQUIPMENT ON VEHICLE.

The vehicles used for the mobile substations are of the flush deck type and enable the layout shown in fig. 6 to be adopted. It will be seen that the outdoor transformer is mounted transversely above the bogie at one end of the vehicle, while the rectifier cylinders are arranged in line on the longitudinal axis of the wagon.

The rectifiers are housed in a ventilated compartment to which access is gained through doors leading from the control compartment. The switchgear compartments contain the E.H.T. oil circuit breaker, the main choke, high-speed circuit breaker, and the control cubicle. Entry to the control compartment (fig. 7) is by steps on the side of the vehicle, similarly the incoming E.H.T. supplies and the outgoing positive and negative terminal connections can be made on either side of the wagon according to the requirements of the site where it may be in use. The E.H.T. incoming terminals are arranged horizontally at roof level, the D.C. terminals and plug sockets being arranged horizontally in recesses at floor level. Connection to the permanent substation is effected by high voltage T.R.S. flexible cable, both for the 10 kV and 1,500 volt connections. In each permanent substation there is an isolating switch for the 10 kV mobile substation connection. To preserve the appearance of the vehicle and to conform to the loading gauge requirements of the railways, the conservator tank on top of the transformer is designed to follow the contours of the roof of the wagon.

In order to maintain proper working temperatures in the rectifier compartment, particularly as the substation may be subjected to extremely cold weather and is exposed to the elements

Fig. 7.—View of operating platform of a mobile substation.

on all sides, the air inlets to the rectifier fans are provided with a heating grill which is thermostatically controlled. To meet summer operating conditions four extractor fans are arranged in pairs on the sides above, and in line with, each rectifier cylinder. Only two fans

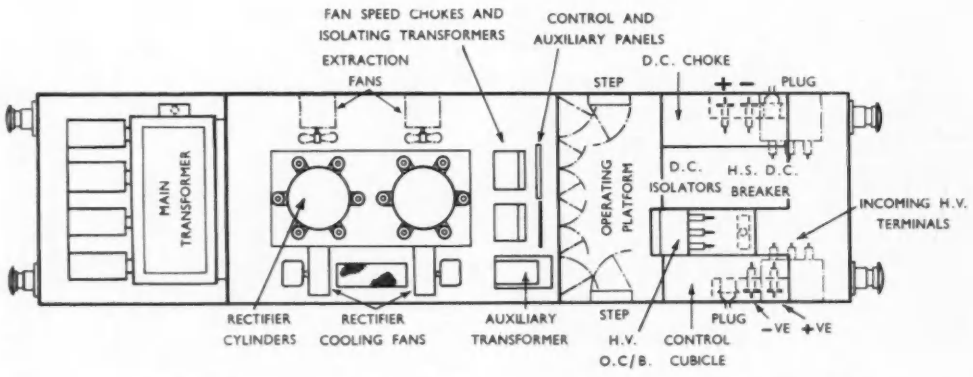


Fig. 6.—Layout of rectifier equipment, control gear and ventilation of 1,224 kW, 1,530 volt mobile substation.

are shown in fig. 6 for the sake of clarity. The operation of these fans is temperature controlled, while the rectifier cooling fans proper are regulated by means of fan speed control chokes. Thus the temperature of the whole chamber is under thermostatic control.

The installation work was carried out in one of the maintenance depots of the Netherlands Railways and fig. 8 shows one of the rectifier cylinders being lowered into position during the building of the mobile substation. The neat appearance and attractive finish of the substations, which are painted white, can be seen from fig. 2.

OPERATIONAL EXPERIENCE WITH THE MOBILE SUBSTATIONS.

Testing on Site.

On completion, the substations were immediately put on to normal working duty. The first purpose for which they were used was the calibration of track feeder overload relays on a new line where the equipment was subjected to overload 'kicks' up to 10,000 amps. without any basic load. After a few minor adjustments the equipments have continued to function without any special attention and have now completed three years of 1,500 volt trouble-free service.

Influence of A.C. Network Harmonics.

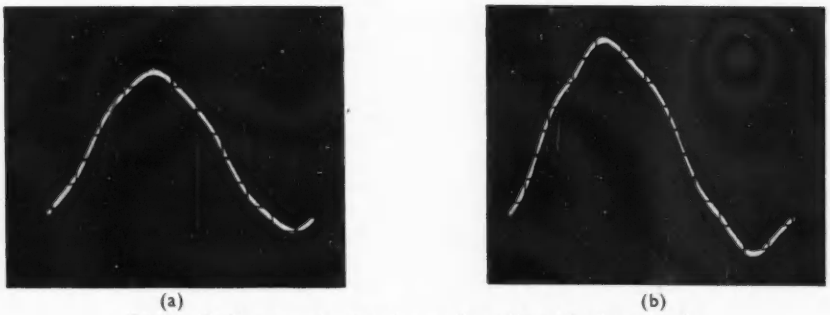
Advantage was taken of the mobility of these substations to investigate certain technical problems which arose from the nature of the power network in Holland, and the existence of a large connected 6-phase rectifier load. For example, while a unit at Utrecht in the centre of Holland showed perfect load sharing between the rectifier cylinders under all conditions of load, the same unit when stationed at Tilburg in the south showed a tendency to slight unbalance of load between the two rectifiers in one direction at one time of the day, and in the opposite sense at other times. Oscillograph investigations showed that this was caused by a pronounced change in the A.C. wave form due to the behaviour of the 5th harmonic, whose amplitude was accentuated by a star/star connection of the A.C. network power transformers. Not only was there a slight accentuation of these harmonics, but a change in their phase occurred at about 7 o'clock each evening; fig. 9 shows the waveform before and after this time. Attempts were made to find the origin of this phenomenon but no reliable evidence could be obtained to suggest any explanation. It is possible, of course, that the origin lies in Germany or Switzerland, as the main transmission line is connected to these countries. Following upon these experiments it has been found that, although the fault did not lie with the rectifier equipment, it was possible to rearrange the rectifier connections so as to give perfect balance at all loads independently of the behaviour of the 5th harmonic.

Parallel Working with Existing Substations

Some interesting tests were carried out to observe the parallel running of one of the mobile substations at Uitgeest with the 6-phase perma-

Fig. 8.—1,530 volt, air-cooled, steel tank pumpless rectifier being lowered into its compartment during construction.

nent substation at the same site. It was found that the load sharing between the two substations was relatively good over the range checked. With a load of 950 amps. on the 12-phase mobile unit the permanent equipment carried 600 amps. A more comprehensive test was taken at Blauwkapel with the purpose of determining the load sharing between the G.E.C. mobile equipment and the local permanent equipments, and to investigate whether the parallel working of the permanent equipment at Utrecht Noordstation influenced the load sharing.



(a) (b)

Fig. 9.—Oscillograms showing change of waveform of voltage supply.
(a) before 19.00 hours. (b) after 19.00 hours.

Because of the difficulties of obtaining steady measurements under actual running conditions, it was decided to make these tests under static loading conditions by making a temporary short circuit of the overhead line at a considerable distance from the substation so as to provide a current path with a resistance of about 1 ohm. A number of tests were taken with the mobile substation and the local permanent substation each working alone, then both in parallel with and without the station at Utrecht Noord sharing the load. Opportunity was also taken to study the effect of changing the transformer tappings on the mobile rectifiers. The results of these tests are given in fig. 10 where curve 1 shows the regulation of the mobile substation, curve 2 the regulation of the permanent substation and curve 3 that of the mobile substation with its transformer on a higher tapping, i.e. a greater number of primary turns to give a lower D.C. output voltage.

It was found that the influence of the substation at Utrecht Noord was very slight, but that the difference between the regulation of the mobile substation and the permanent substation was greater than could be accounted for purely on the basis of 6-phase and 12-phase operation. The difference in load caused by the discrepancy of the regulation curves is not of such magnitude that special measures need be taken, but from curve 3 it is clear that in a situation where heavy overloads may be expected the mobile unit could be placed with its transformer on a higher primary tapping so as to give perfect load sharing with a total load of the order of 4,000 amps.

It was decided on the basis of these experiments that, as the mobile substations tended to take a slightly greater share of the load, the regulation of the second pair of mobile equipments should be increased to 4·5 per cent. This is more in line with recent British practice. These substations now approaching completion in Holland are identical in rating and performance with the first two except for the steeper regulation curve to give improved load sharing.

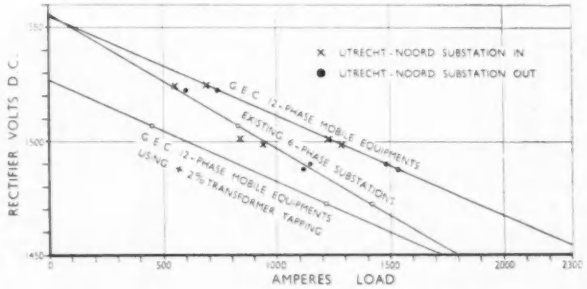


Fig. 10.—Regulation diagram showing load-voltage curves of 12-phase and 6-phase permanent substation and influencing adjacent substation.

NEW PERMANENT SUBSTATIONS.

Specification of Equipments.

Because some of the original switchgear and transformers were recovered from Germany and are being used again, these components determined the technical specification of the new permanent substations (fig. 11). The transformers are rated at 1,800 kW and are provided with tappings at plus and minus 2 per cent and 4 per cent.

The rectifiers themselves are rated at 1,224 kW, 1,530 volts D.C., the complete equipment having overloads of 150 per cent load for 2 hours, during which period a series of further overload peaks, including two of 4,000 amps. for one minute, are called for, and a regulation of 2·7 per cent. To conform to the features of the equipment installed before the war, fault protection by means of arc suppression was also specified.

Design Features of the Equipment.

The Dutch transformers were arranged for 6-phase rectification using interphase transformer connections, but were double wound to give two sets of windings on the D.C. side. That meant that although two air-cooled steel tank pumpless rectifiers were to be used with each transformer they would be operating as a 6-phase unit, and, furthermore, they would

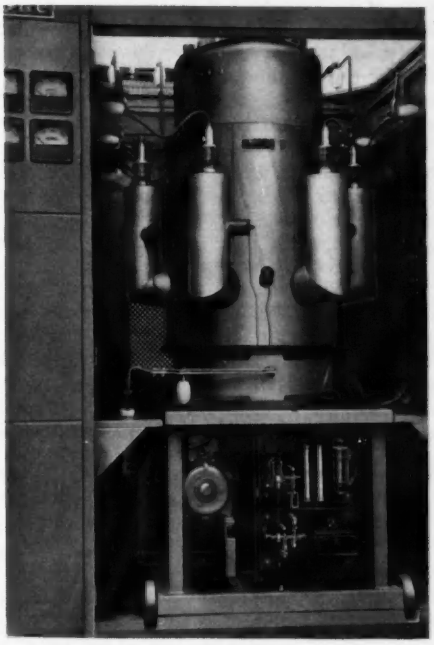


Fig. 12.—1,500 volt, air-cooled steel tank pumpless rectifiers fitted with control grids for arc suppression mounted in cubicle in permanent substation.

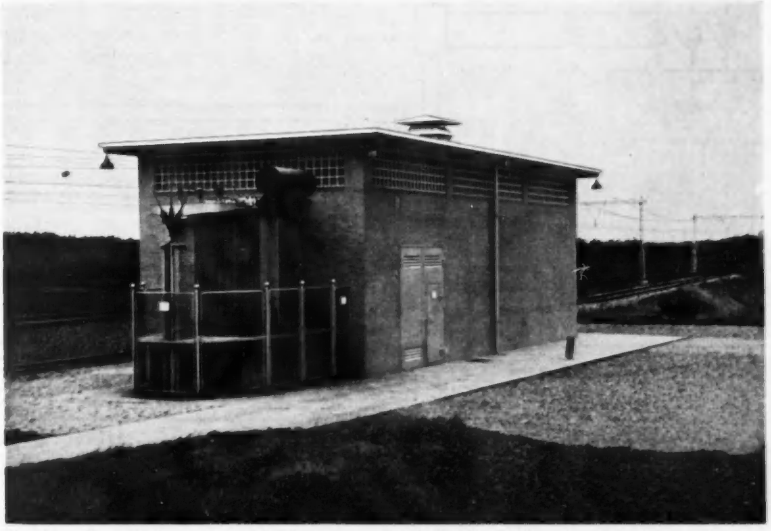


Fig. 11.—One of the new standard permanent 1,224 kW, 1,530 volt substations at Ryssen seen from the transformer end.

be provided with control grids for arc suppression. Because the main transformers were not fitted with a tertiary winding the auxiliary supplies for the rectifier and the control gear were obtained from an auxiliary transformer operated from the same supply as the main transformer.

The rectifiers shown in fig. 12 are mounted on withdrawable trucks and housed in sheet steel cubicles of the modern brake press construction in which the sheet metal parts are flanged over at the edges to provide a structure of considerable rigidity and pleasing appearance. The rectifier fans are equipped with speed control by saturable chokes which regulate the voltage applied to the fan motors in accordance with the load on the rectifiers. Between the two rectifier cubicles is a panel on which are four flush mounted instruments consisting of two main and two auxiliary ammeters showing the output current from each cylinder and their respective auxiliary anode circuit currents.

Arc Suppression by Electronic Control.

The arc suppression gear, the circuit of which is shown in a simplified form in fig. 13, is electronically operated and therefore practically instantaneous in its action. The operation of the arc suppression is based upon the principle that a negatively biased grid placed in the arc path close to the anode will prevent the arc conducting to the anode so long as it has not already been established. Thus the arc cannot transfer from one anode to the next and is finally extinguished when its current falls to zero.

The normal conduction of each anode is produced in the present case by providing for each grid a sinusoidal bias whose positive half-cycle occurs at the time the corresponding anode should become conducting. This supply is derived from a 6-phase auxiliary transformer supplied via phase adjusting transformers from the main 3-phase auxiliary transformer. To prevent conduction of the anodes and bring about the arc suppression, a suitable amount of excess negative bias derived from a metal oxide rectifier circuit is superimposed upon the sinusoidal bias to drive all the grids strongly negative.

The arc suppression is operated on the G.E.C. triple frequency tripping principle in which a 150-cycle signal derived from current transformers on the A.C. side is increased in the event of fault or excessive overload current flowing to actuate the grids of "biased off" thyratrons which, on being released, cause the excess negative bias to be applied to the control grids of the rectifiers. Because the 150-cycle signal operates in either half wave the maximum delay in terms of the 50-cycle supply

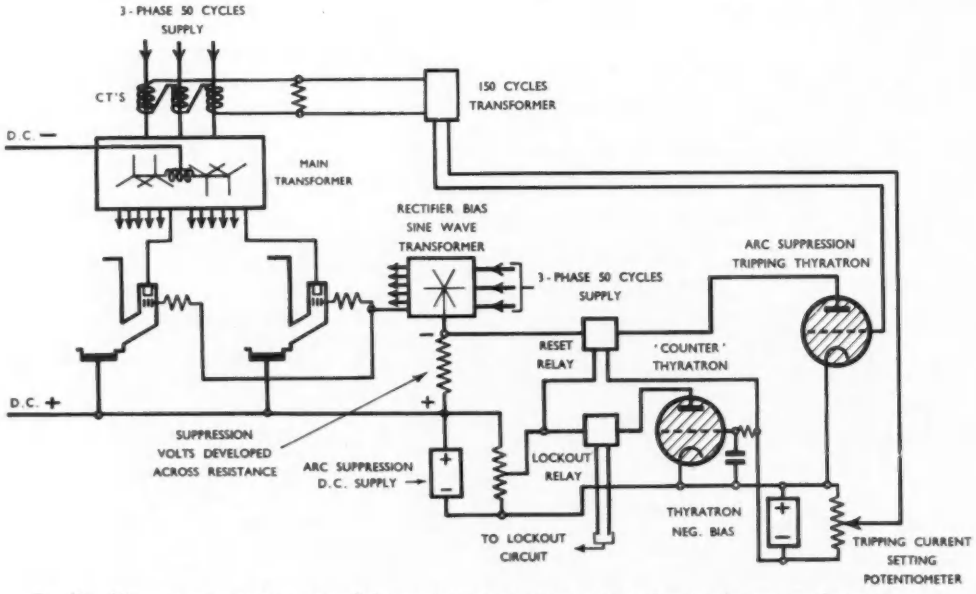


Fig. 13.—Diagrammatic arrangement of electronic arc suppression circuit showing derivation of tripping signal from A.C. supply and application to twin cylinder rectifier equipment as used on Netherlands Railways.

which can arise in the application of the arc suppression is $\frac{1}{6}$ cycle. Incorporated in the electronic circuit are means for ensuring a locking out of the rectifier in the event of the electronic gear being called upon to operate an excessive number of times in quick succession. Another feature included in the arc suppression gear is a time delay unit to cover the heating up time of the thyratrons before they come into service. This unit serves to delay the operation of the auto-reclose relay for a suitable period after the "on" signal has been given. Fig. 14 shows the complete equipment, including the test push buttons which enable the correct functioning of the arc suppression to be checked at any time.

Before these rectifiers were installed, the opportunity was taken at the Works to test the arc suppression gear thoroughly. These trials included tests under no-load and short circuit conditions and with fault currents exceeding 13,000 amps. Fig. 15 is an oscillogram typical of the results obtained, and shows the removal of the 1,500 volt D.C. from the line upon the application of the negative bias when actuated by the short circuit current.

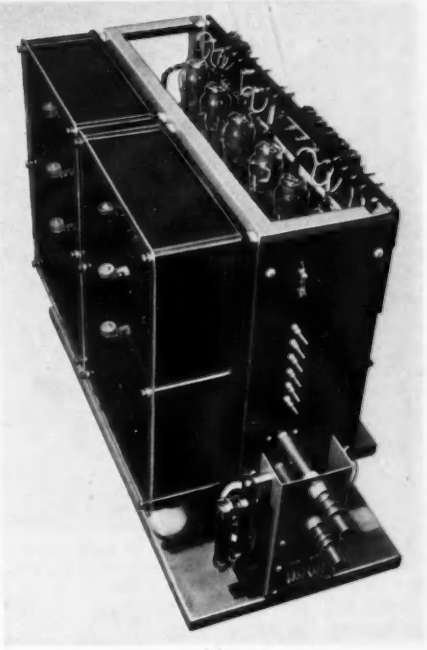
GENERAL PROTECTION.

Further interlocks had to be arranged to prevent the oil switch being closed before the arc suppression gear, the cooling fan motors and the excitation circuit come into operation.

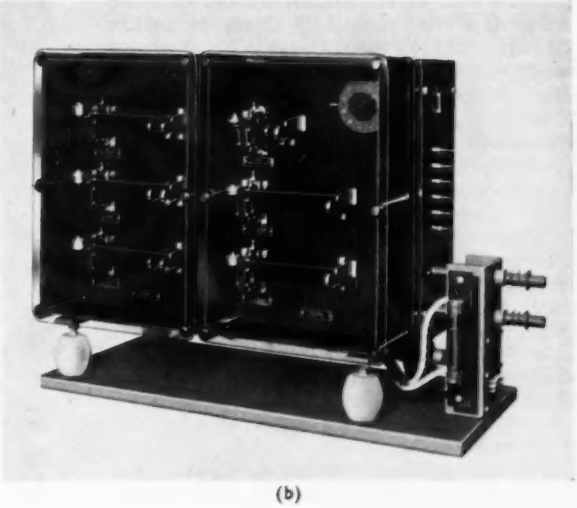
Arrangements are made for the equipment automatically to lock out in the event of the three unsuccessful attempts to start. Locking out will also take place immediately on recurrence of any of the following faults: excessive transformer temperature, Buchholz relay operation, failure of voltage supply on arc suppression gear, repeated operation of arc suppression, failure of valve heater supplies in the arc suppression gear, operation of overload relay of cooling fan motor.

In addition, the breakers will be tripped and the auto-reclose relays put into action again by overloads on the A.C. side, reverse current on the D.C. side, or excitation failure.

As well as the operation of the arc suppression gear in the case of excessive current, means are provided to apply the negative bias also when the station is shut down in the normal way so as to prevent unnecessary wear on the oil circuit breaker contacts.



(a)



(b)

Fig. 14.—Two views of the electronic arc suppression gear showing (a) test push buttons for manually checking the operation of the equipment, and (b) side view showing reset, lockout and other relays incorporated with arc suppression gear.

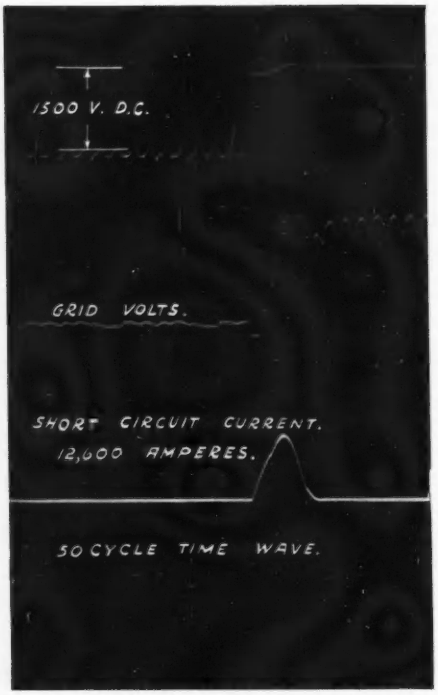


Fig. 15.—Oscillogram showing the working of the electronic arc suppression gear in interrupting a short circuit current of 12,600 amps.

Layout of Substation.

There are both double and single unit substations, and, in the former, the rectifiers are mounted in pairs immediately inside each of the end walls (fig. 16), the D.C. and A.C. switchgear occupying a central position opposite to each other on each of the long walls.

Because of the nature of the ground, the substations are built on a concrete raft independently of the transformer rafts, individual rafts being supported on twelve hollow concrete piers. They are attractive and well-proportioned buildings with flat roofs, the larger ones having three equally spaced ventilators for the outlet air ; the inlet air is taken through louvred doors at either end of the long wall of the substation. Each double unit substation is 24·54 metres long by 4·46 metres wide by 5·5 metres high, thus providing a spacious enclosure with ample room for air circulation.

Performance.

The installation of the first permanent substation was completed and the equipment put into service in January, 1951. The complete line between Utrecht and Hengelo with nine more equipments was inaugurated for electric working during the following May. Since that time the system has been in operation under main line conditions of load, and, so far as can be ascertained, the electronic arc suppression gear has not been called upon to function except under deliberate test conditions.

Acknowledgments.

As will be seen, the building of four mobile substations and sixteen permanent equipments with plant of both Dutch and British manufacture was an undertaking of no small magnitude and the excellent performance of these equipments is due largely to the skill and goodwill shown by the engineers from both countries in carrying out their respective tasks. Accordingly, the Company gives ready acknowledgment to the Netherlands Railways and in particular to Mr. E. van der Hoek, Mr. P. J. Koster, Mr. J. E. J. Ankersmit and their Engineering Staff.

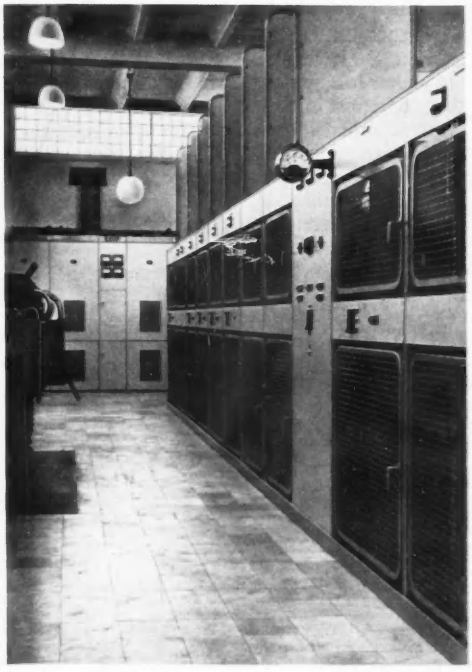


Fig. 16.—Interior view in the permanent substation at Ryssen, showing the 1,224 kW, 1,530 volt rectifier equipment in cubicles at the far end.

Recent Developments in Diamond Technology: Wire-Drawing Dies and Graded Diamond Powder

By R. E. LEEDS, M.B.E.
G.E.C. Research Laboratories.

The word "diamond" holds a mysterious fascination for many people. Those concerned with the fabrication of this material into useful tools for industry, are, however, aware of the many difficulties inherent in working the hardest known material in the world. In the field of diamond wire-drawing dies, an improved method of piercing a diamond with an electric spark is described. An account of a complete process for grading diamond powder is also given.

AFTER a new product has passed from experiment to manufacture, a third phase begins. This takes the form of a search for possible improvements in the process whereby losses may be cut down, production speeded up and difficult manipulative processes made easier for operators, consistent always with maintaining a high standard of product. Diamond dies for drawing wire are no exception to this sequence of events and, after a state of steady manufacture has been reached, experiments have been, and are still being made to solve outstanding difficulties and to seek improvements.

In making a diamond die there are nine distinct operations, seven of which are shown diagrammatically in successive stages in fig. 1. The various stages are given below, and reference to fig. 2 is made in order to explain the nomenclature used to identify each section of the profile of a die :

1. Cutting flat parallel faces and viewing windows on natural stones (fig. 1).
2. Piercing the "entrance" (figs. 1 and 2).
3. Piercing the "approach" (figs. 1 and 2).
4. Piercing the "reduction angle" (figs. 1 and 2).
5. Locating and countersinking the "exit" (figs. 1 and 2).
6. Piercing to break-through the "exit" (figs. 1 and 2).
7. Polishing the profile (figs. 1 and 2).
8. Sizing the "bearing" (fig. 2).
9. Mounting in the metal case.

Diamond is chosen for wire-drawing dies on account of its extreme hardness and resistance to wear. A wire-drawing die is a stone in which a conically-shaped hole reduces the diameter of a wire by plastic deformation of the metal, induced by local circumferential pressure from the sides of the tapered hole as it is drawn through. So far, diamond is the best material available to stand up to such a rigorous condition. Despite the fact that it is a crystalline allotropic modification of carbon, which is itself a very soft material, diamond is the hardest mineral in the world. Diamond is also a unique substance in that, at present, there is nothing harder available with which it may be cut, so that diamond must be used to cut diamond. For this purpose a certain granular crystalline form of diamond called "boart" is crushed into powder and separated into grades of definite particle size distribution. The coarser grades are used for cutting and shaping, while the finer grades are used for smoothing and polishing.

Consideration is now given to the piercing of a particular zone of a drawing die, namely the "reduction angle" (see fig. 2). This has frequently to be pierced to produce a drawing die with a bore diameter of 0·0004 in. (10·16 microns*) which means that the pierced diameter can only be of the order of 0·0003 in. (7·62 microns) since the die must be polished before wire can be drawn through it. A piercing operation of this dimension would be made on a

* A micron is one thousandth part of a millimetre and is therefore, approximately one twenty-five thousandth part of an inch.

machine similar in design to the one shown in fig. 3 which is not unlike a miniature lathe. A steel needle accurately aligned to the shaft of the headstock revolves at 6,000 revolutions per minute while the stone, with the " entrance " and " approach " already pierced and filled with graded diamond powder suspended in an oil vehicle, is reciprocated against the end of the needle. Under impact of hammer blows, the diamond powder is crushed between the end of the needle and the base of the piercing in the die stone. This reduces the powder in size and at the same time slowly pierces the die stone, the profile being maintained by continually resharpening the needle. When a die bore of only 0·0003 in. is required, the maximum grain size of diamond powder which can penetrate to the base of the piercing is of the order of 0·0002 in. (5·08 microns). This is virtually a polishing powder. The ground parallel portion at the end of the needle can only be 0·0003 in. diameter and should the impact force exceed 0·02 oz. the needle bends. A hundred or more hours of this operation are therefore needed to pierce a 0·0003 in. bore into a die stone. A typical curve of piercing times is shown in fig. 4.

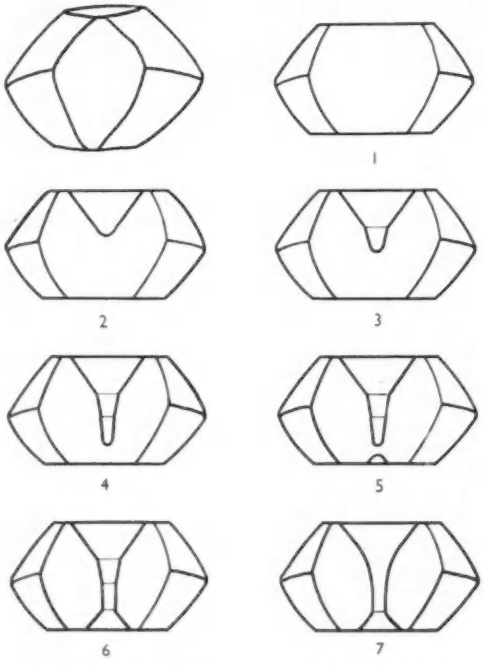


Fig. 1.—Schematic arrangement of die operations.

It will be readily appreciated that, in order to make wire-drawing dies on a production scale by the method described, large numbers of expensive machines are necessary. A way of

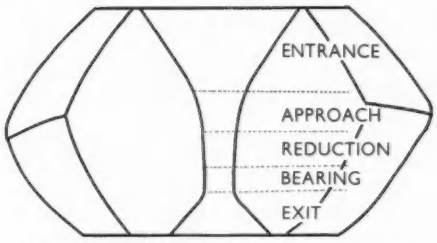


Fig. 2.—Nomenclature of various zones in die.

overcoming this disadvantage has been shown,* by which holes can be rapidly pierced into diamond with an electric spark. Since diamond is an electrical insulator, many hundreds of volts would be required to strike and maintain an arc in air around the outside of even a comparatively small stone. When such high voltages are applied, graphitisation of the diamond surface usually takes place and the stone appears blackened. The piercing produced, quite apart from being large in diameter and irregular in contour, is also blackened and any control on quality is exceedingly difficult to attain. A low voltage arc offers a solution to the problem and can be accomplished by immersing the stone in a conducting liquid. For this purpose a weak saline solution may be used in which a stone immersed just beneath the surface of the liquid will become electrically conducting over its surface. To complete the electrical circuit through the saline bath two electrodes are essential, one to rest on the stone where the spark is required and the other immersed deeply in the solution. With this arrangement it is possible to spark the " reduction angle " zone into a die stone with a bore as small as 0·0002 in. (5 microns) diameter and the time taken is a little over two hours. For larger diameters up to 0·001 in. (25·4 microns) the time taken is even less and the spark process, therefore, represents a saving of more than 50 to 1 in the time of piercing. A drawing die produced by this method is shown in fig. 5 in which the zone farthest from the top is the one produced by the spark method. The two zones " entrance " and " approach " (see fig. 2) are pierced in a normal manner with the correct grades of diamond abrasive and form a cavity into which the point

* British Patent Specification No. 597,392.

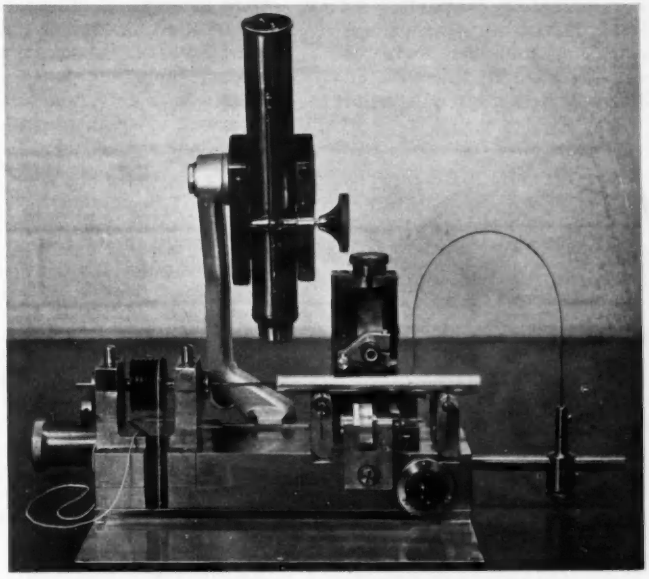


Fig. 3.—Standard die piercing machine for fine bore dies.

of a pre-sharpened needle rests at the apex. The cavity is filled with salt solution by the immersion of the stone and a correct adjustment of liquid level will permit a spark zone to be maintained at the tip of the needle. The point of the needle is retained during the piercing operation by automatic electro-etching of the metal from which it is made.

A typical spark apparatus is shown in fig. 6, with the needle-grinding equipment on the left-hand side. The apparatus consists essentially of a slowly rotating glass dish to hold the salt solution with a platform in the centre to support the stone (seen in detail in fig. 6a). Axiality and levelling adjustments are provided to enable the initial piercing in a stone to be accurately aligned, thereby ensuring continuity of profile. The needle, preground to the correct angle, is suspended on a delicate spring to ensure correct contact pressure with the stone. Contact pressure between stone and needle can be varied by moving the lever at the top of the apparatus, and alignment of needle to stone is made by three centralising screws. The electrical equipment attached to the apparatus is quite simple and is housed in a convenient position behind the spark apparatus. The voltage range, which varies according to the diameter of the die bore required, lies between 60 and 240 volts and this is conveniently obtained from a normal 230 volts A.C. supply through a " Variac " with a delivery of 0 to 270 volts. An ammeter is provided to measure the current.

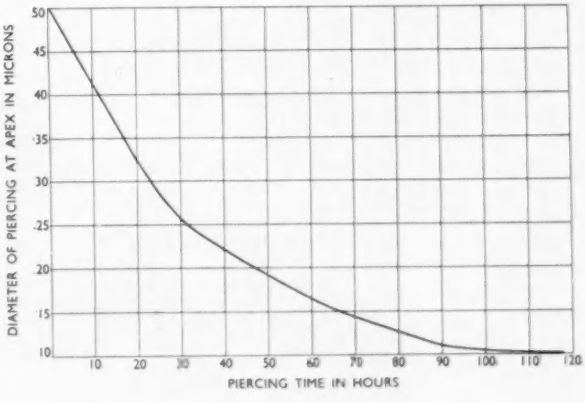


Fig. 4.—Curve of piercing times.

A method has been described for speeding-up the piercing of the " reduction angle " zone of a diamond wire-drawing die, accomplished without the use of diamond powder. Yet many of the operations in making a die still require diamond

Fig. 5.—Profile of die bore. Lower zone produced by the electric spark method.

powder and a considerable amount of experimental work has been carried out to establish a reliable process of grading.

The preparation of diamond powders for cutting or polishing is essentially a process of sorting crushed diamond into different grades, each grade exhibiting a distribution of particle size within a definite range. One particular grade may have a particle size range from 0-2 microns while another may be from 80-100 microns.

Reference was made earlier to the fact that the diamond used for making powders is known as " boart ". This is the name under which all diamond, unusable for various reasons as a single piece, is classified. Like diamond, boart is measured by carat weight. A metric carat is 200 milligrammes and there are, therefore, 5 carats to a gramme or 141·75 carats to one ounce.

The first stage in preparing diamond powders consists in crushing the boart in order to obtain particle sizes as nearly as possible within a desired range (usually from 0 to 500 microns). The method employed for crushing has an important bearing on the shape of the particle produced. Some powders will be " splinty " in shape like thin pointed slivers, while others can be produced as robust " blocky " particles capable of hard work without premature disintegration. This latter type of powder can be made in an impactor mill, shown in fig. 7, consisting of four sealed cylinders each capable of crushing 500 carats of boart. The inside faces of the cylinder ends are cupped to form anvils on which the boart is crushed by two steel balls acting as hammers as the cylinders slowly rotate. By varying the milling time, the peak of particle size distribution can be moved from the centre to either the finer or coarser fractions according to grade demands.

After the crushing operation, it is essential to clean the powder chemically in order to remove all impurities, the chief of which is iron from the impactor. On account of the relatively high cost of boart, it is necessary to avoid all losses as

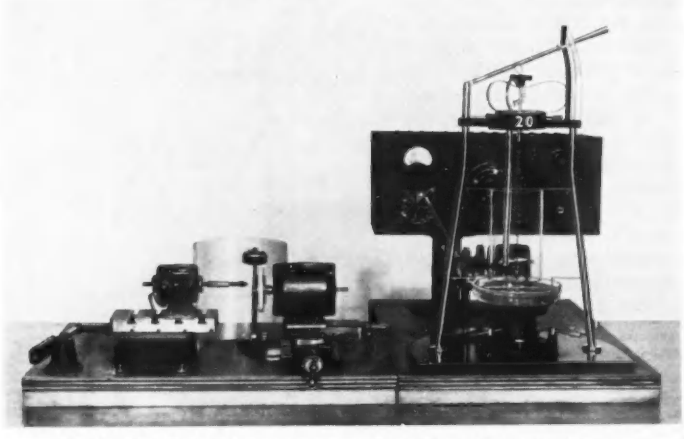


Fig. 6.—Spark piercing apparatus and needle grinding equipment.

far as possible, and the cleaning operation is that during which most loss can occur. The powder is carefully cleaned in various acid solutions in order to ensure that only diamond remains. Finally the powder is washed free from acid and dried ready for grading.

The grades of diamond powder produced fall into two distinct classes, the sieve sizes and the sub-sieve sizes. Fortunately it is possible to produce a range of powders down to a nominal 76 microns by sieving through sieves which comply with the British Standard 410—1943. This gives details for testing sieves and, if they are regularly examined to see they do not fall outside the permitted tolerances, uniform powder grades can be regularly produced. Hand sieving can be both erratic and laborious, so that a machine specially made for the purpose is used. This machine, shown in fig. 8, is the " Sherwen " electro-magnetically operated sieve shaker of Fraser & Chalmers manufacture. A stack of twelve sieves can be handled at one time and the machine speedily produces constant sievings without damage to the mesh. The sieved powders are finally washed in alcohol to remove any very fine particles adhering to the grains so that clean graded powders are obtained.

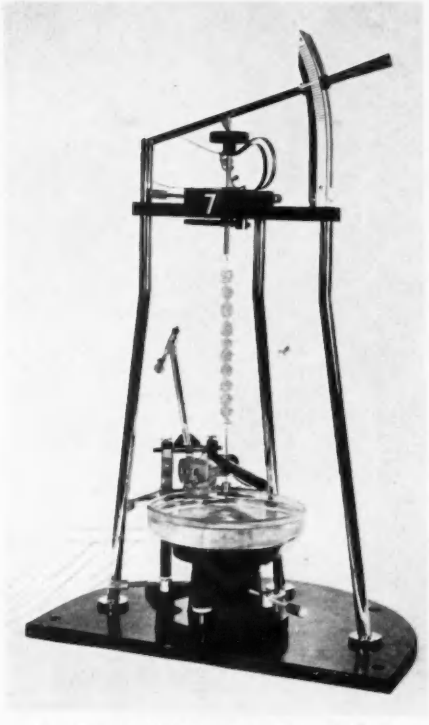


Fig. 6a.—Detail of apparatus shown in Fig. 6.

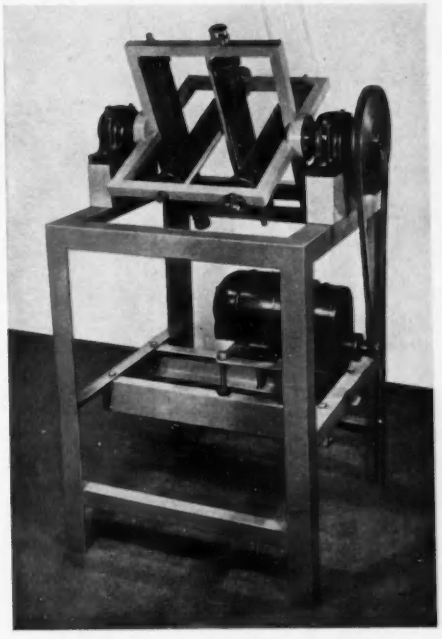


Fig. 7.—Impactor for crushing diamond boart.

Difficulties associated with powder grading are more numerous when dealing with the division of a sub-sieve fraction. This fraction, which passes through a B.S.200 mesh sieve, is divided into ten separate grades representing the most important used in diamond die manufacture. The division is made either by a process of sedimentation or elutriation. Both processes are similar in that they depend upon the relative motion of individual particles and a fluid. Prior to more recent experimental work on the grading of diamond powders, sedimentation was possibly the most popular method used. The process was simple to carry out by mixing diamond powder with olive oil in a shallow dish and decanting after a given time for settling. This practice led to very imperfect grading as shown in Table 1.

TABLE 1.

SEDIMENTATION (200 ml OLIVE OIL).

Settling Time	Grade Expected	Grade Obtained
10 mins.	40–80 microns	1–200 microns
2 hrs.	20–40 microns	1–200 microns
4 hrs.	10–20 microns	1 – 30 microns
8 hrs.	5–10 microns	1 – 20 microns
30 hrs.	2 – 5 microns	1 – 15 microns
12 days	1 – 2 microns	1 – 5 microns
3 months	0 – 1 microns	0 – 5 microns

Experiments have shown the desirability of using both elutriating and sedimentating methods for producing accurately graded powders to-day. Both methods have comparative advantages and disadvantages and the best possible use is therefore made of each. The sub-sieve powder is divided into five separate grades by elutriation. The first grade is a 0-10 microns fraction which is sub-divided into five grades by sedimentation. All powder above 10 microns is divided by the elutriator into five finished grades, a division of the larger particles from the sub-sieve powders.

The elutriator used for this purpose is a modified form of the Cooke short column elutriator, adapted to the grading of diamond powders. A three-unit installation used for this purpose is shown in fig. 9.

Elutriation is a method of grading particles by means of an upward flow of fluid. When the rate of liquid flow is accurately maintained and stable conditions are obtained in the hydraulic fractionating column, closely graded powders are obtained as shown in Table 2.

TABLE 2.

ELUTRIATED POWDERS

Grade No.	Micron Range
50	8-18
60	16-30
70	28-43
80	40-58
90	50-76

Division of the finer fraction, extracted by elutriation from the sub-sieve powder, is made

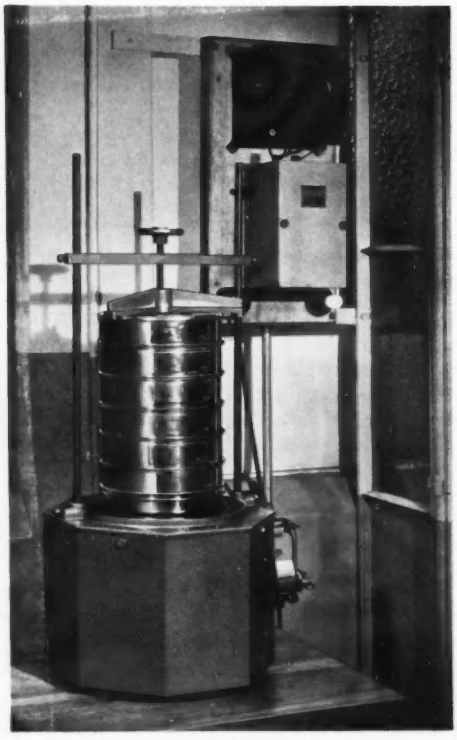


Fig. 8.—Stack of sieves on Sherwen electro-magnetically operated sieve.

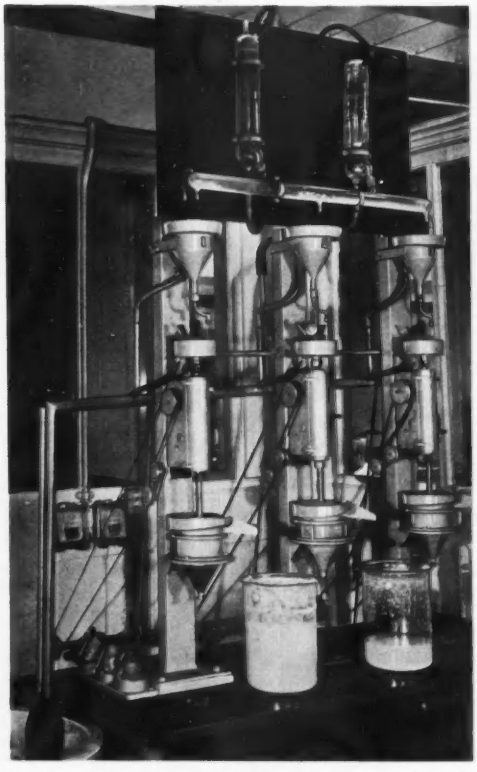


Fig. 9.—Short column elutriator for grading diamond powder.

by sedimentation. If this fraction were divided into different grades by the elutriator, the time taken would be very long and the apparatus very difficult to control to avoid inaccurate gradings. Therefore, the sedimentation method is used, but this is also very slow, especially if it is carried out in the best possible manner. This difficulty has been overcome by sedimenting the powder by centrifugal force and in the apparatus used (fig. 10) the process is speeded up several thousand times. In Table 1, a figure of 12 days is quoted for obtaining a powder of 1-2 microns and this time can be reduced to 20 minutes by using a centrifuge. Quite apart from the advantage gained by the increase in speed, the accuracy of the grading is also much greater, as shown in Table 3.

TABLE 3.
CENTRIFUGED POWDERS

Grade No.	Micron Range
5	0 – 1
10	0·5 – 2
20	1·5 – 4
30	3·0 – 6
40	5·0–10

Accurately graded diamond powders are not only absolutely essential for making diamond wire-drawing dies, but have a wide field of applications in many other industries. Although the cost of diamond powder is relatively high, this is easily offset by the increase in speed with which it cuts, grinds and polishes many different materials. Owing to this characteristic the demand for diamond powders is continually increasing.

Investigations are continuing on many outstanding problems associated with diamond dies and graded diamond powders. One problem, in particular, which is receiving attention at present is the determination of the best method of grain size assessment. Sizing is usually achieved by examining a small sample from each grading under a microscope, and measuring every fragment within a given area in the field of the eyepiece. From such measurements, which may, in some instances, number several thousands, a distribution curve is plotted. The grading quality is then judged from the shape and spread of this curve. If powdered diamond took the form of small spheres of uniform diameter the problem would be an easy one, but the particles are always irregular in shape and of varying thickness. In any one

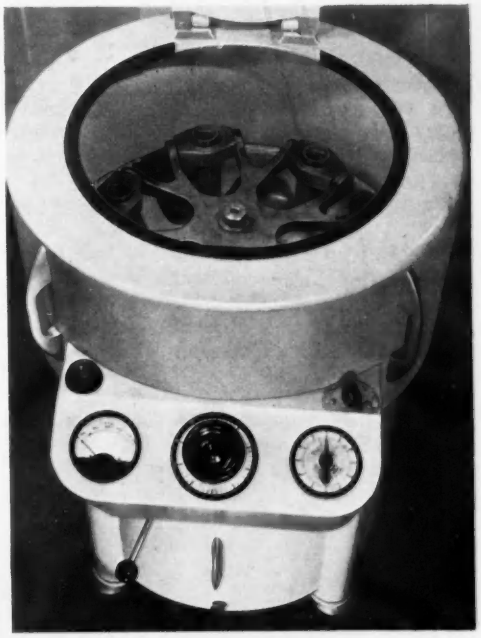


Fig. 10.—Centrifuge for grading diamond powder.

grade, therefore, if the grading has been correctly carried out, all the particles will have the same weight to within close limits, while their projected area will vary greatly. The problem of reliable quality assessment by the measurement of irregularly shaped fragments graded by weight therefore remains to be solved.

Although only a few of the problems in diamond technology currently being dealt with have been mentioned here, they should serve to show the trend of present developments in this important field.

Flying Shear Control at the Steel Company of Wales

By S. A. G. EMMS, B.Sc.,
Witton Engineering Works.

INTRODUCTORY.

IT is impossible to exaggerate the importance of The Steel Company of Wales to this country at the present time. Expansion of export trade, which is so essential to the national economy, is dependent upon a sufficiency of sheet steel being made available to industry, and this must be achieved without detriment to defence commitments. The huge Abbey Works, the inaugural opening of which took place about twelve months ago, and the new tinplate plant at Trostre which came into operation more recently, will go a long way towards meeting this ever-growing demand for sheet steel and tinplate.

It is of interest to recall the very large amount of electrical and mechanical plant which the G.E.C. has supplied for the Margam, Abbey and Trostre Works. This equipment includes 18,000 kW of generating plant ; 9,600 kW of rectifiers ; turbo-blowers for blast furnaces ; main drives for two temper mills, two skin pass mills and a pickle line ; mill auxiliaries for the slabbing mill, and continuous hot strip mill, and many hundreds of motors for cranes, blast furnaces, coke ovens, conveyors and the like. In all,

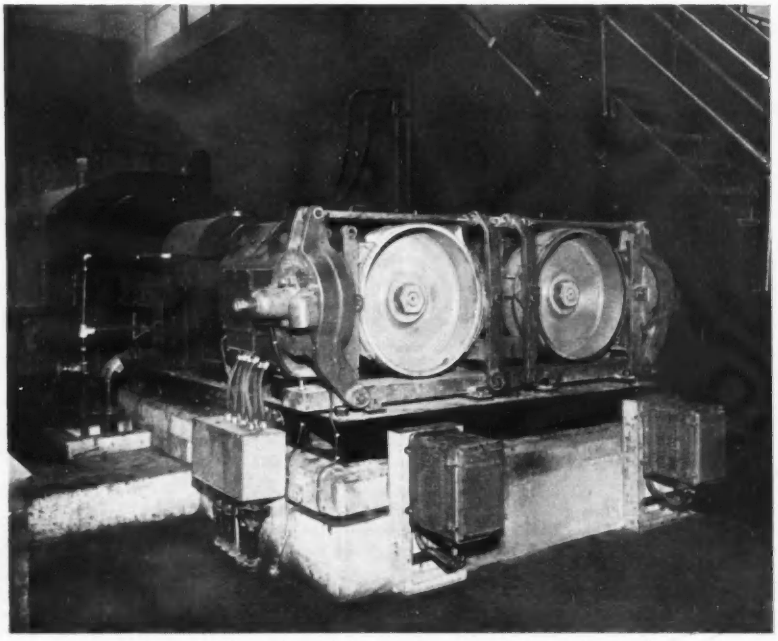


Fig. 1.—The flying shear of the continuous hot strip finishing mill.

over 900 mill type motors with a total output of some 38,000 h.p. as well as a corresponding number of other types of motor representing a further 15,000 h.p. are involved in this scheme. Marshalling yard and road lighting and extensive communication systems covering telephones, a radio telephone equipment and sound equipment installations were also undertaken.

The Abbey mills are equipped to produce hot and cold-rolled steel strip, sheets, and plates up to 74 ins. wide, the 80-inch continuous hot strip mill being planned for an initial output of 1,250,000 tons of hot-rolled strip a year. The very high rolling speeds of the modern continuous hot strip mill bring in their train new problems of increasing difficulty which must be solved by the manufacturer of the electrical equipment. As strip speeds increase, so does the need for accuracy and rapidity in the control of the mill assume greater importance. This is particularly so in the case of the flying shear, the speed of which must bear a constant relationship to that of the mill, if sheets are to be sheared within the desired limits of length. It is with the control of the flying shear that this article is primarily concerned.

THE ROTARY FLYING SHEAR.

The rotary flying shear is situated immediately following the last finishing stand of the continuous hot strip mill. It comprises a top and bottom drum each of which carries a shear blade. Two mill type motors with forced-ventilation (fig. 1) are coupled through single reduction gears to the top drum which in turn drives the bottom drum through a 4-to-3 reduction gear. The motors are rated at 0/150/430 h.p., 0/230/660 volts, 0/450/1,300 r.p.m., and each receives power from its own 125/360 kW D.C. generator. The two generators form part of two 6-machine motor generator sets (fig. 2) which are located in the motor-room and serve also to supply the electric drives of the run-out tables and down coilers.

The shear is designed to cut hot steel strip up to $\frac{1}{4}$ in. thick by 74 ins. wide, the strip speed varying from 900 to 2,000 ft. per minute. Although up to the present the shear has only been used for cutting sheets, it is capable of performing any of the following duties :

(1) Accurately shear the strip into sheets ranging in length from 15 ft. up to 30 ft. rising in increments of $\frac{1}{2}$ in.

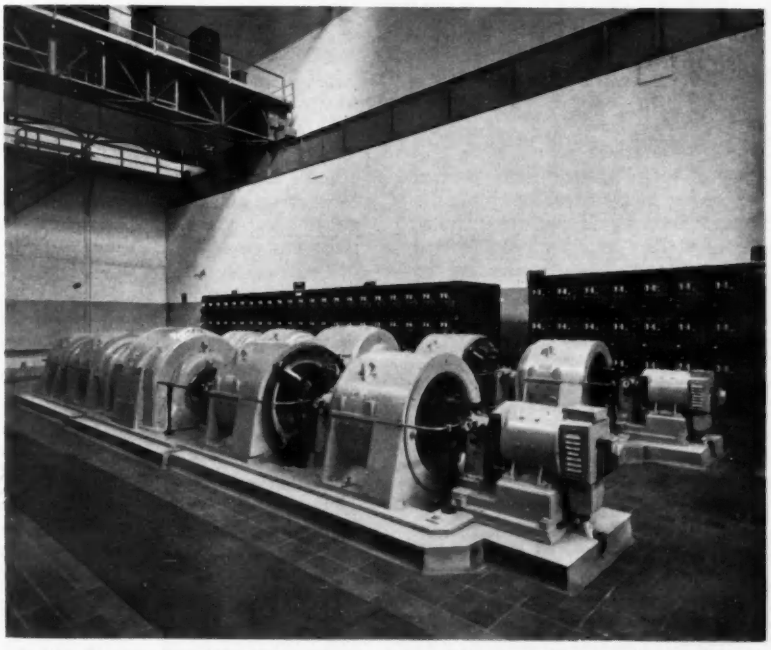


Fig. 2.—The two 6-machine motor generator sets which supply the flying shear, coiler and run-out table motors.

(2) Crop the front end of the strip only.
(3) Crop the tail end of the strip only.
(4) Crop the front and tail ends of the strip.
(5) Crop the front end of the strip followed by shearing into sheets.

It is operated from the control desk in the finishing mill pulpit. Selector switches on the desk determine the duty of the shear, and whether starting is to be by the hand control switch or automatic by means of load relays in the armature circuits of selected finishing stand motors. Additional desk controls are provided for inching and testing. After completing its duty cycle, the shear is brought to rest automatically, with the blades in their correct relative positions in readiness for the next operation.

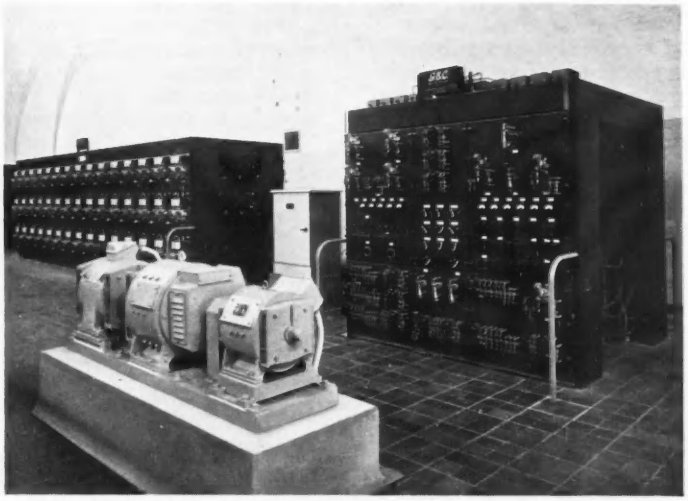


Fig. 3.—The cascade exciter set, main contactor board and electronic cubicle for the control of the flying shear.

FUNCTIONS OF THE CONTROL GEAR.

In the control of the shear two distinct sets of conditions have to be met according to whether the shear is cutting sheets or cropping the ends of the strip.

When shearing the strip, the length of sheet is determined by the relative speed of the shear and the last finishing stand so that the shear must respond rapidly and accurately to the slightest variation in the speed of that stand.

On the other hand, the essential condition for cropping is that the shear should be started up at the precise moment that will enable it to accelerate up to speed at a predetermined rate so that the blades arrive in the correct position for cropping the end of the strip without producing excessive scrap.

SYSTEM OF CONTROL.

To meet the exacting requirements of the flying shear drive, it was decided to adopt the cascade exciter system which has been developed for service where control must combine the advantages of speedy response with high sensitivity and complete stability.

The cascade exciter, as its name implies, is composed of two or more machines in cascade, the more usual equipment consisting of a pilot exciter, a main exciter, and driving motor.

Apart from its laminated field circuit, the cascade exciter does not differ from an ordinary D.C. machine either in principle or structure and thus requires no special knowledge or experience to maintain. It is, however, designed to provide very rapid operation and considerable change in output for a very small change in the field current of the pilot machine.

In addition to a control field winding, the pilot exciter is usually provided with several others which may include series and shunt bias windings to prevent hunting, and a current limit winding which, in conjunction with metal rectifiers and a potentiometer, limits the armature current of the

controlled machine rapidly and accurately to a predetermined value.

Greater sensitivity may be obtained by incorporating an electronic amplifier to magnify any change in the current fed to the control field winding of the pilot machine and this refinement is provided for the flying shear control. It is interesting to record, however, that in service the cascade exciter has provided such a high degree of accuracy in the control of the shear, that sheets are sheared to within the tolerance of plus or minus $\frac{1}{2}$ in. and for this reason the amplifier has not yet been brought into regular use.

The cascade exciter set for the flying shear, together with the main contactor board and electronic cubicle are installed in the motor-room and are illustrated in fig. 3.

OPERATION WHEN SHEARING.

From the simplified schematic diagram (fig. 4) it will be seen that the two shear motors and their generators are connected in series and that the speed of the motors is controlled by regulating the excitation of the generators, the fields of which are supplied from the cascade exciter set. Field forcing contactors (FFC) in the field circuits of the shear motors are used on starting. Links (not shown) enable any machine to be isolated in the event of a fault, so that the shear may continue to operate at reduced power.

The control field *A* of the pilot exciter is energised through metal rectifiers by a double saturable reactor, which is so biased that any change of current in the control coils will cause the impedance of one half to rise and of the other half to fall and so alter the output of the reactor.

Closing of the shear contactors (SC) applies the full voltage of the mill tacho-generator *M* across the control coil of the reactor which at once supplies power for energising the control field *A* of the pilot machine of the cascade exciter. This in turn excites the main generator fields so that an increasing current flows through the armatures of the shear motors. When this current reaches a safe maximum, as determined by the setting of the current limit potentiometer, the

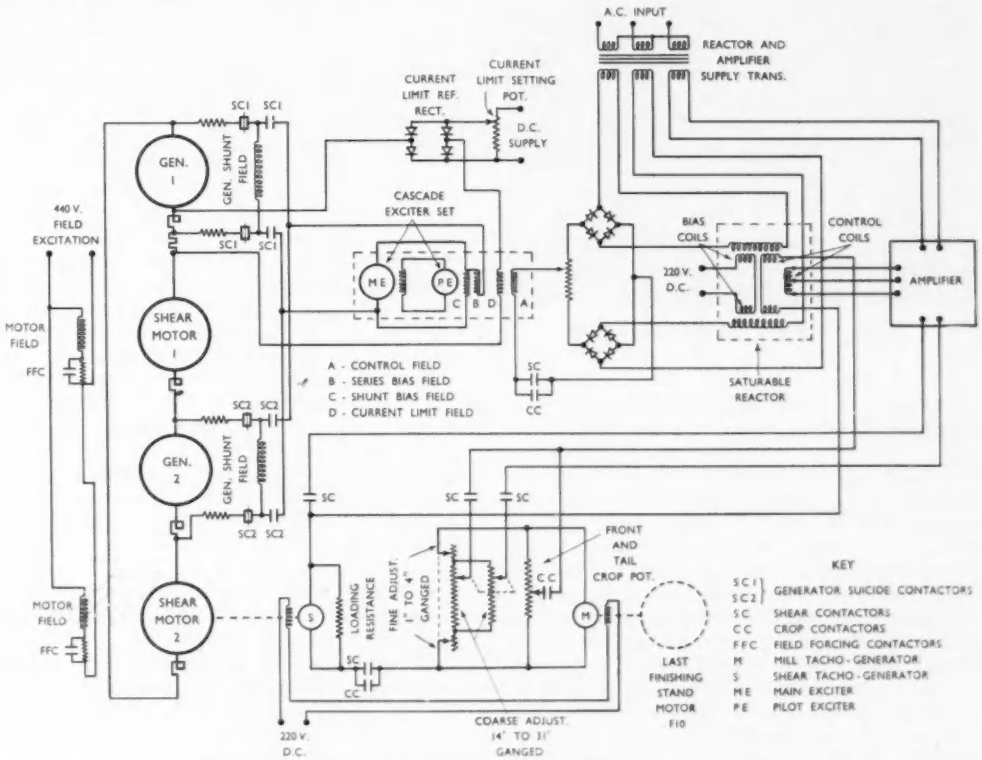


Fig. 4.—Simplified schematic diagram of the flying shear control.

winding *D* of the pilot exciter is strongly excited. This winding opposes the control winding *A* and thus limits the output of the cascade exciter set which in turn limits the excitation of the main generators and so prevents any further increase in the current fed to the shear motors. Thus, the shear motors are accelerated under conditions of

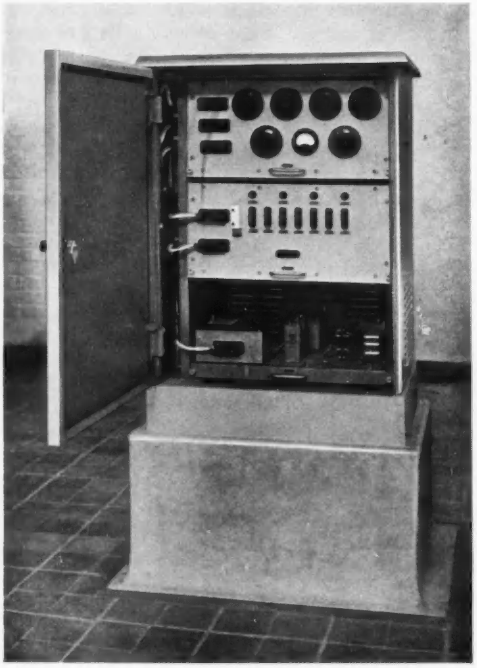


Fig. 5.—Interior of the electronic cubicle.

accurately controlled torque until the difference between the predetermined fraction of the voltage of the shear tacho-generator *S* and that of the mill tacho-generator *M* creates a state of balance in the control circuit when the shear motors will run at the required speed. Thereafter, any variation in the relative speed of the shear motor and the last stand motor of the mill will disturb the state of balance in the control circuit and the speed of the shear motor will be adjusted accurately and rapidly until the correct speed relationship is re-established.

The selected fraction of the voltage of the shear tacho-generator *S* decides the speed of the shear motor and consequently the length of sheet produced. It is determined by coarse and fine rheostats mounted on the control desk, and calibrated from 14 ft. to 31 ft. and from 0 to 4 ins. respectively.

The electronic amplifier is shown in fig. 5. It will be seen from fig. 4 that when this component is in circuit it energises a separate control coil of the double saturable reactor, so that the system of control continues to function in the manner already explained.

The full schematic diagram of the shear control is reproduced in fig. 6.

OPERATION WHEN CROPPING.

The operation of the control system is the same for cropping as for shearing except that, in this case, a fixed fraction of the voltage of the shear tacho-generator *S* is used. Its value is such that the final speed of the shear motor corresponds to a blade speed equal to or slightly above the strip speed.

The starting of the shear is accurately timed by an electronic timer, in conjunction with load relays in the armature circuits of the appropriate finishing stand motors.

The operation of the timer may be followed by reference to fig. 7. Normally the relay *S*1 is de-energised, so that the capacitor *C* is connected in series with the resistor *R*4 across the H.T. supply. Since the grid and the cathode of the valve *V*1 are at approximately the same potential, i.e. the voltage drop across *R*10 is made approximately equal to the voltage tapped off the potentiometer *R*1-*R*2-*R*3, this valve will be conducting and its anode and cathode currents will produce potential drops in the resistors *R*8 and *R*10 respectively. The resistors *R*8, *R*9 and *R*11 form a potentiometer across the H.T. supply, the grid of the valve *V*2 being connected to the junction of *R*9 and *R*11. Hence the grid and cathode potentials of this valve are determined, their values being such that this valve is cut off.

On receiving an initiating signal from the load relays of the selected stand motors, the relay *S*1 is energised and remains closed until the operating cycle of the shear is completed. The changeover contacts of this relay now connect the positive plate of the capacitor *C* to the tapping on the potentiometer *R*1-*R*2-*R*3 and the negative plate to the grid of the valve *V*1 so that this valve is cut off immediately. This produces a sudden rise in the anode potential and a sudden drop in the cathode potential. As a result, the grid of the valve *V*2 is made positive and this valve begins to conduct, thus energising the relay *S*2 which opens its contacts in the control circuit and a moment later, closes its normally open contacts thereby energising the relay *S*3 which is retained by a contact on the relay *S*1. Imme-

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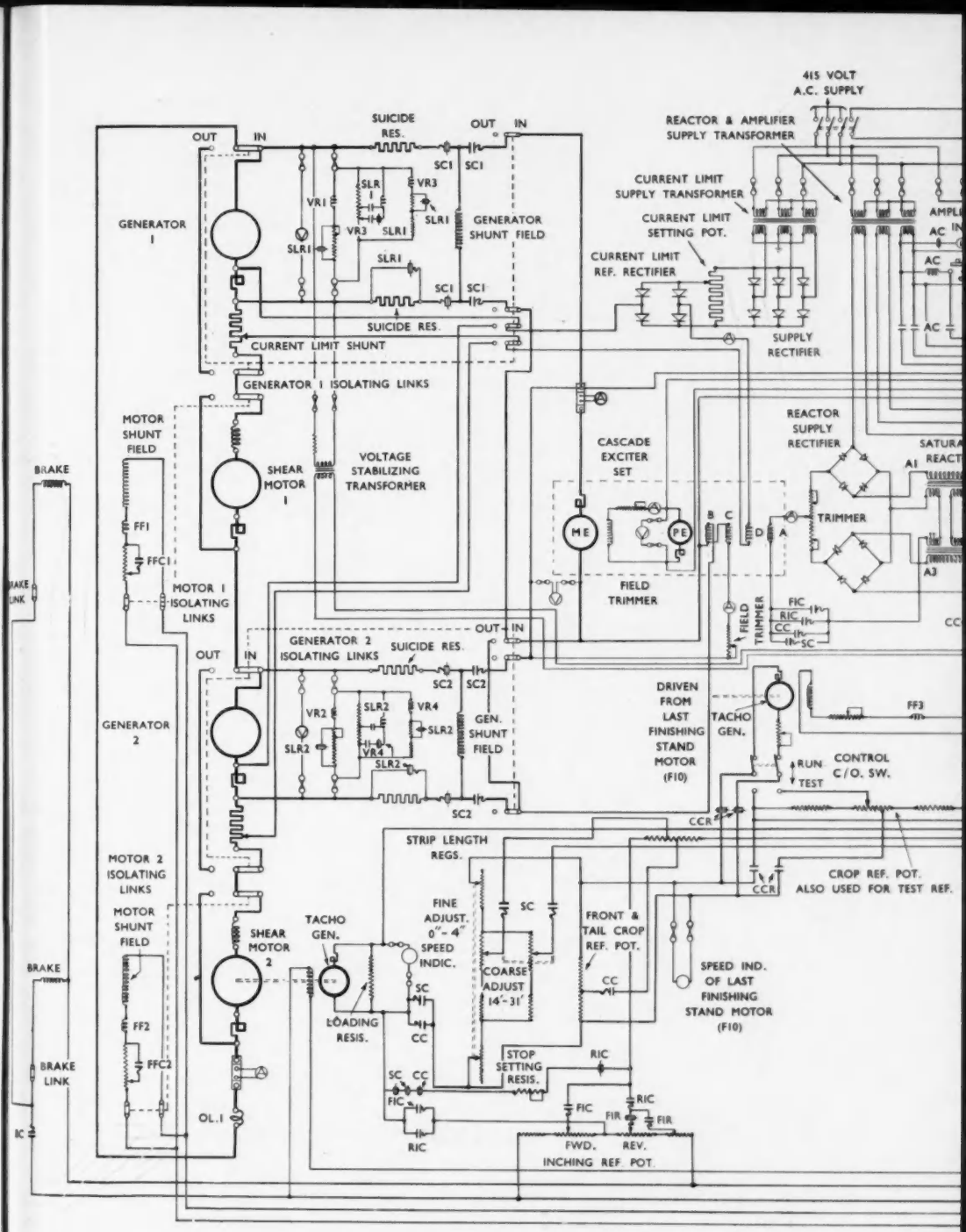
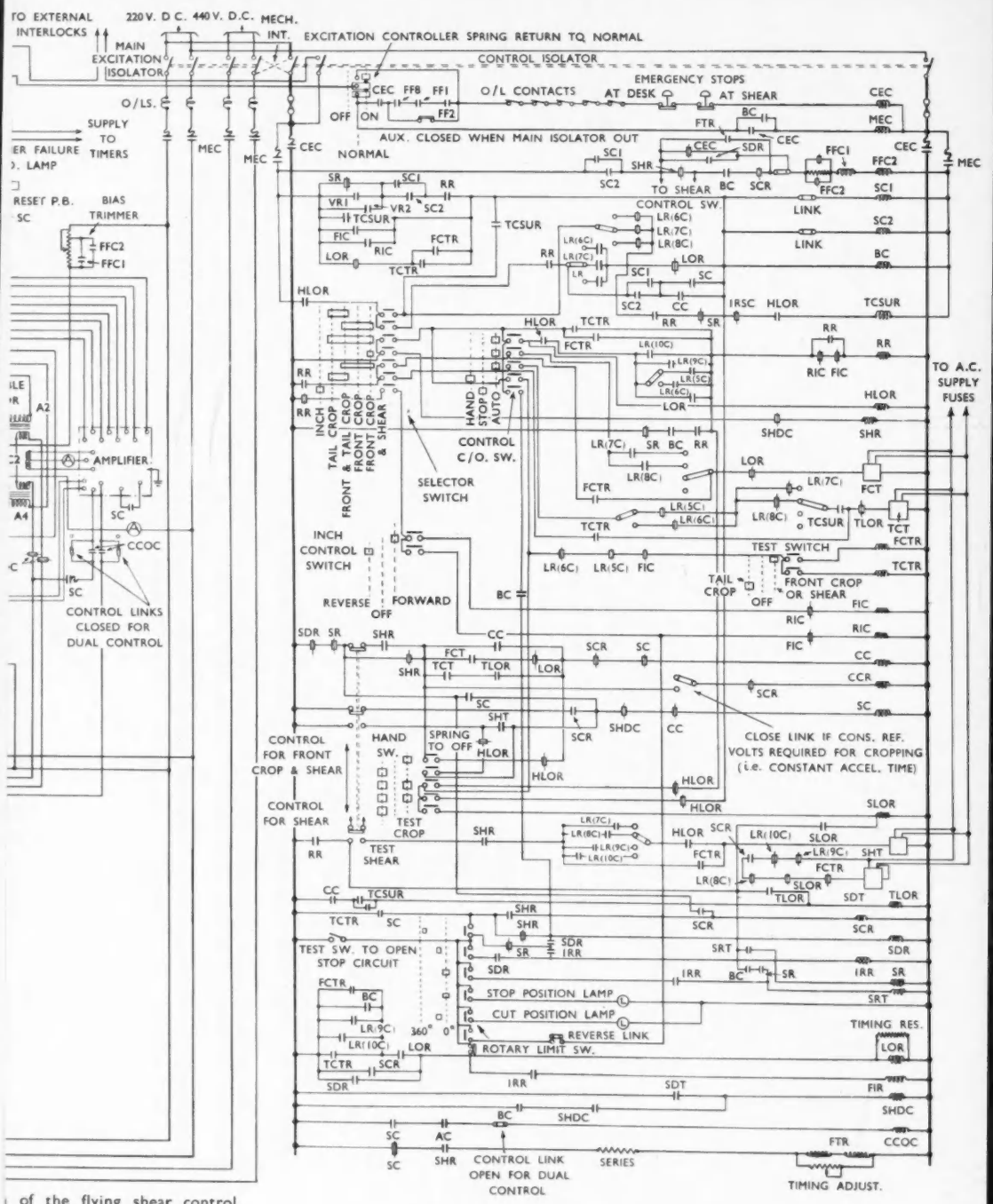


Fig. 6.—Full schematic diagra

Symbol	Apparatus
FFC 1-2	Motor 7 and 8 field forcing contactors.
FIC	Forward inch contactor.
RIC	Reverse inch contactor.
CEC	Control excitation contactor.
MEC	Main excitation contactor.
SC 1-2	Gen. 7 and 8 suicide contactors.
BC	Motor brake contactor.
TCTR	Tail crop test relay.
TCT	Tail crop time delay.

Symbol	Apparatus
FCTR	Front crop test relay.
FCT	Front crop time delay.
FF 1-2	Motor 7 and 8 field failure relay.
SDT	Shut down time delay.
SHDC	Shut down contactor.
SR	Stopping relay.
RR	Running relay.
IRR	Inch reverse relay.
SDR	Slow down relay.

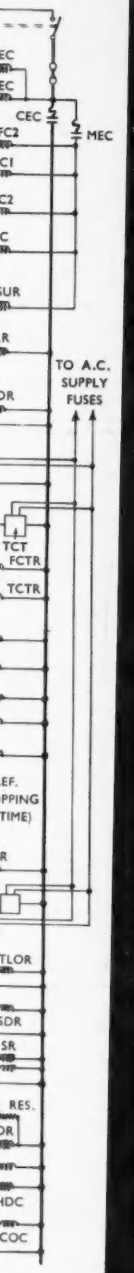
Symbol	Ap
LOR	Front crop lock
VR 1-2	Gen. 7 and 8 v
CC	Crop contactor.
SHR	Shear relay.
LR 5C-	Load relay co
LR 10C	board).
OL 1	Main overload r
OL 2-3	Main excitation
OL 4-5	Motor shunt fie



of the flying shear control.

Symbol	Apparatus
TCSUR	Tail crop set up relay.
SCR	Shear contactor relay.
SHT	Shear time relay.
SC	Shear contactor.
SLR 1-2	Gen. 7 and 8 suicide limit relays.
FF 3	F 10 tacho gen. field failure relay.
CCR	Crop contactor relay.
HLOR	Hand lockout relay.
TLOR	Tail lockout relay.

Symbol	Apparatus
SLOR	Shear lockout relay.
CCOC	Control changeover contactor.
FTR	Forcing timing relay.
FIR	Fast inch relay.
AC	Amplifier supply contactor.
ME	Main exciter.
PE	Pilot exciter.


CEC
MEC
TO A.C.
SUPPLY
FUSES
TCT
FCTR
TCTR

diately the valve $V2$ starts to conduct, a voltage drop is again produced in the resistor $R10$, the effect of which is to make the changeover action cumulative. Furthermore, the capacitor $C1$ provides a low impedance path for the voltage surge created by cutting off valve $V1$ so that a larger proportion of the change in the anode voltage of this valve is transferred to the grid of the valve $V2$ than would otherwise occur. Hence the rate of changeover is increased still further, and in practice an extremely rapid trigger action is obtained.

The capacitor C now begins to discharge through the variable resistor RV until the grid potential of the valve $V1$ approaches its cathode potential when this valve begins to conduct again. This causes the common cathode potential of the two valves to increase, and the potential of the grid of the valve $V2$ to fall. Once again the action is cumulative and the valve $V2$ is rapidly cut off, thus de-energising the relay $S2$.

As the contacts of relay $S3$ are still closed, the effect of opening the control circuit contacts of relay $S2$ is to impart a signal to the flying shear control circuit and close the crop contactors. As soon as the shear has completed its operation, the relay $S1$ is de-energised so that the relay $S3$ opens and the timer is ready for the next operation.

The precise timing of the device depends upon:

(1) The voltage at which the capacitor C is charged, i.e. the H.T. voltage which is stabilised by neon lamps.

(2) The value of resistor $R2$ in the potentiometer $R1$-$R2$-$R3$. This is used for the initial calibration of the timer only.

(3) The value of the capacitor C which is fixed.

(4) The variable resistor RV by means of which the time interval is adjusted to the required value.

The electronic timer can be adjusted to an accuracy of 1/100th second, which corresponds to a length of 4 ins. when the strip is travelling at 1,800 ft. per minute. The correct settings for the electronic timer to correspond to different strip speeds are tabulated in the control pulpit.

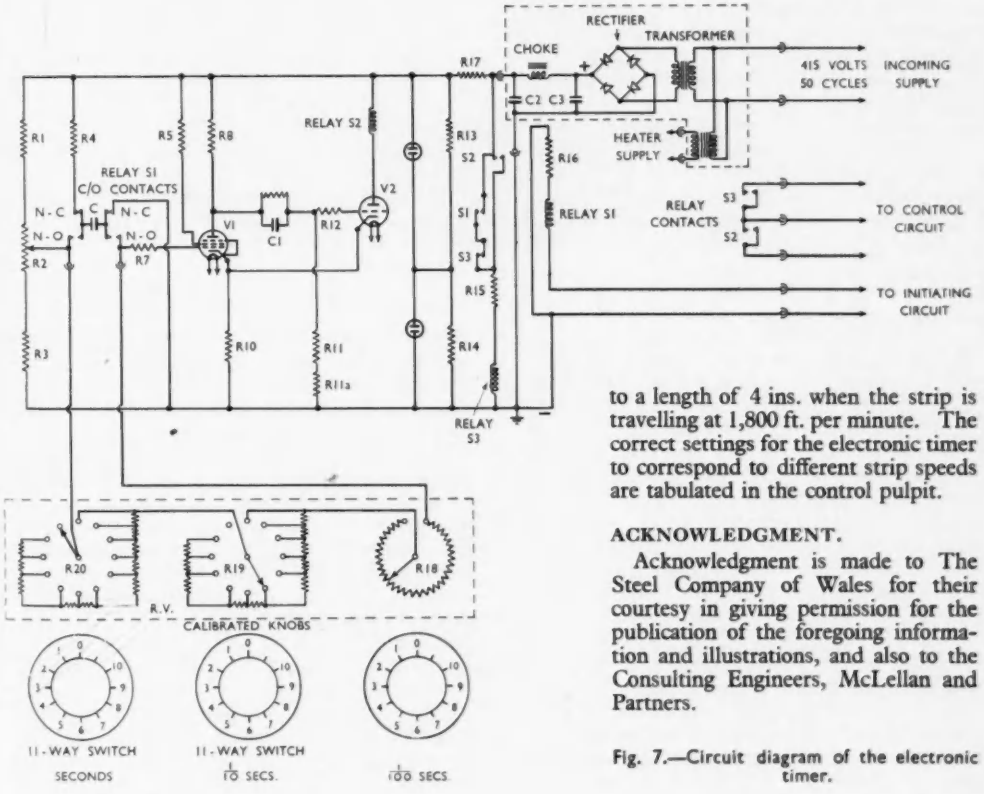


Fig. 7.—Circuit diagram of the electronic timer.

ACKNOWLEDGMENT.

Acknowledgment is made to The Steel Company of Wales for their courtesy in giving permission for the publication of the foregoing information and illustrations, and also to the Consulting Engineers, McLellan and Partners.

The Production and Application of Magnetic Powders

By G. R. POLGREEN, M.B.E., B.Sc., M.I.E.E.
Salford Electrical Instruments, Ltd.

Magnetic powder cores have been established for several years as important components for all telecommunication equipment and loading coils for telephone cables. As a result of the development of new magnetic powders, there are now further important applications in other branches of electrical engineering. Thus, powder cores are now being made in quantities for low-loss coils used in electrical power applications, measuring instruments and television scanning equipment. Very fine powders can now be produced with good permanent magnet properties.

Many of these new materials have important uses at the present time in overcoming the severe shortages of non-ferrous metals which are essential constituents of most high-grade magnetic materials in both solid and sheet form; special reference is therefore made to various grades of pure iron powder and to the new copper-nickel-iron alloy (Gecalloy 111) which renders possible a considerable economy in the use of nickel especially for cores employed in telephone transmission circuits.

This article describes the methods and equipment developed by The General Electric Company Limited and its subsidiary company, Salford Electrical Instruments, Limited, for the manufacture of iron and alloy powders and compares their properties with other powders and magnetic materials now available. Details are given of the chemical methods originated by this company for producing magnetic powders of all kinds to give low losses and higher stability and reference is made to recent developments which permit the manufacture of permanent magnets from very fine iron powder.

1. INTRODUCTION.

ALTHOUGH electrical engineering is a comparatively modern activity of mankind, resulting from the discoveries of electromagnetism in the early nineteenth century, some knowledge of magnets and magnetic materials has existed for over 2,000 years. Apart from the historic and scientific interest in the subject of magnetism, magnetic materials are of the greatest importance to all branches of electrical engineering because they constitute a major part of most of the machinery, instruments and equipment made in the electrical industry today.

From the early inventions of the pioneers of this industry, electrical engineers and designers have constructed their products from solid mild steel, assembled stampings and hard steel permanent magnets, the resulting designs and performance being to a great extent dependent upon the properties and limitations of these materials. It is now possible, however, to meet many of these technical requirements with cores moulded from magnetic powders, which give improved performance with economy of materials; moreover, these cores can be made into various shapes which cannot be produced with present conventional production materials. Much of the new production technique will be recognised as belonging to powder metallurgy, a technique that has received considerable publicity during the past 15 years, chiefly for making large quantities of small mechanical parts of complex shapes. An essential difference is, however, that these magnetic powders are insulated with ceramic or resin coatings, whereas in conventional powder metallurgy the metal is sintered after pressing.

The advantages and future possibilities of magnetic powder cores, however, are not due to any single factor but are dependent upon a combination of better material and technical properties, improved designs and more economi-

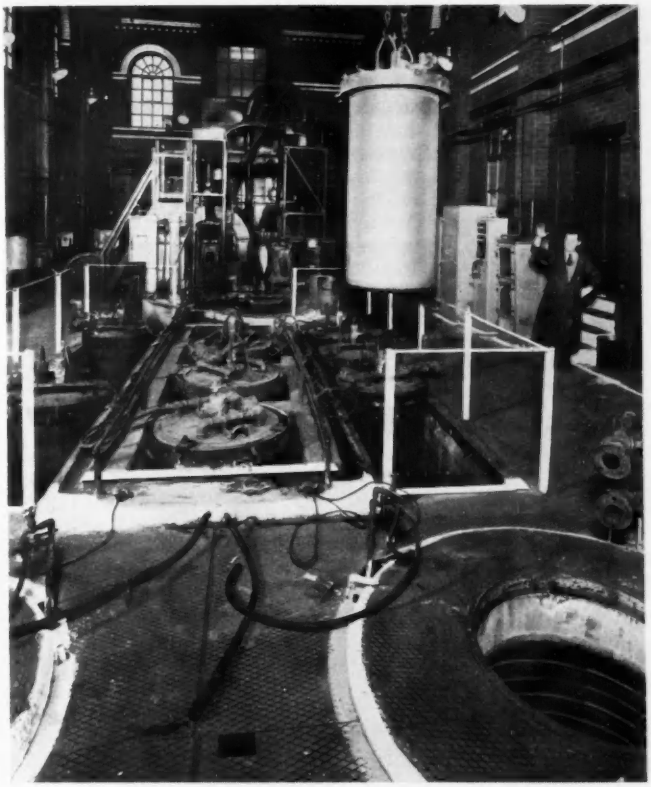


Fig. 1.—Main furnace shop.

cal manufacturing methods. The chief requirement is an adequate supply of a range of magnetic powders, some of pure iron and others of various iron alloys, in order to meet the widespread and complex demands at low and high frequencies for both power and telecommunication uses. This article describes the manufacture of various grades of magnetic powders at the Salford Works of the G.E.C. (fig. 1). The properties of these magnetic powders will be compared with those of others made by different processes and the performance of the resulting powder cores will be briefly considered in relation to the conventional solid materials and with the recently developed non-metallic ferrites.

Most of the magnetic powder now being made is issued for low-loss cores for telephony and radio, but important new powder cores have recently been developed for such diverse applications as indicating instruments, television transformers and scanning coils, and fluorescent lighting chokes. Other types of powder have been produced with excellent permanent magnet properties ; some of these are finding an important use for magnetic recording tape and others can be made, by methods similar to those used in the production of low-loss cores, into permanent magnets with special advantages for many purposes.

The original process for making high-quality alloy powders for magnetic cores by chemical methods was developed at G.E.C. Research Laboratories and was applied to the manufacture of loading coils used in telephone transmission by cable (fig. 2). The first production plant was installed at Salford in 1931 and in due course an additional range of cores was produced for telephone filter coils, radio tuning coils and high-frequency transformers (fig. 3).

The demand for all types of magnetic powder was increased greatly due to the outbreak of the second World War, particularly because the principal material being used for high-frequency cores for radio and radar equipment was carbonyl iron powder imported from Germany. The chemical reduction process made it possible to produce pure iron and nickel-iron alloy powders which give good results up to radio frequencies. Hence a plant was installed at Heywood and started operation early in 1940 to produce several tons of these powders a week. This satisfied all the requirements for the armed forces until a Government plant also became available in 1943 to produce carbonyl iron powder in quantities.

At the end of the war the large supplies of materials and available manufacturing capacity stimulated the development of the powder materials for other branches of electrical engineering, some of which are now in production and are described in this article.

2. REQUIREMENTS OF MAGNETIC MATERIALS.

The diverse requirements of the electrical

industry for magnetic materials may be conveniently divided into three main groups :

(1) Low-loss materials working at low flux density.
(2) Low-loss materials working at high flux density.
(3) Permanent magnet materials (high hysteresis loss).

other cores with closed magnetic circuits, the permeability is of greater importance than for electromagnetic designs with air-gaps or open magnetic circuits. Examples of the latter are small motors, instruments, telephone receivers, etc., and for these the equivalent permeability of the magnetic core and air-gap combined is relatively low.

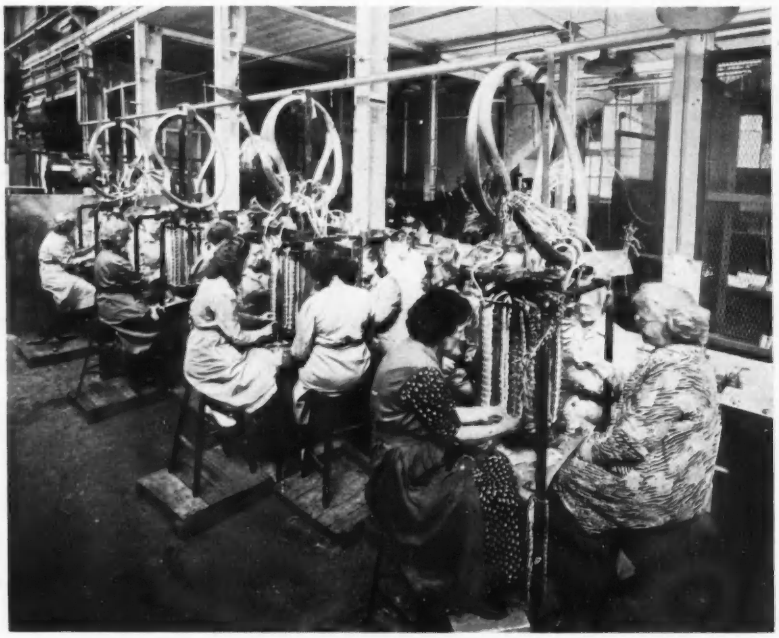


Fig. 2.—Loading coil assembly.

The first group comprises cores for tuning coils, filter coils and loading coils for telecommunication purposes. In these coils the value of current is of the order of microamperes or milliamperes, and hence the magnetising force and flux density are very low. The working frequency is generally very high and so the principal requirements are low losses and adequate permeability at the working frequencies.

The second group includes nearly all magnetic cores in power circuits for which high saturation flux density is the most desirable property. Low electromagnetic losses are also necessary so that the heating effect will be minimised and the efficiency increased, the permeability being kept as high at the working frequency as the eddy current losses will allow. For transformers and

In the third group, permanent magnets, the most important factor is high hysteresis loss which gives the magnet its special property of retaining magnetic energy. This has so far been obtained by using special hard steels and cast ferrous alloys, but good permanent magnet properties can now be obtained from special iron oxides or very fine iron or iron-alloy powders (micropowders) compressed into solid cores.

For group 1 the commercially available magnetic materials with the lowest losses and highest permeability are nickel-iron alloys containing about four-fifths nickel (the trade names of some of these, are for example " Permalloy " or " Mumetal "). For lower permeability cores it is customary to use pure grades of iron which are much less costly than the nickel alloys. In group 2, iron in pure form or alloyed with a

small percentage of silicon is generally used throughout the electrical industry ; such material has the advantage of high saturation flux density with low price. Lower losses can be obtained with a nickel iron alloy containing 40 per cent or 50 per cent nickel ; this gives a high saturation flux density compared with the high nickel group, but at considerably greater cost than silicon steel. Highest saturation values can be obtained by using an alloy of iron with 30 per cent to 50 per cent cobalt, but the high cost and present scarcity of the latter is a severe limitation to its use. It has been shown experimentally in America that extremely pure iron heat treated in hydrogen will give high permeability and lower hysteresis losses than the best grades of high nickel content alloy, but so far these remarkable properties have been achieved only to a very limited extent on a practical scale. However, the pure iron powder cores made by the methods described in this article give lower losses than available sheet steels, and also have a high saturation flux density, thus providing a combination of the desirable properties in both groups 1 and 2 in the above classification.

3. PROPERTIES OF POWDER CORES.

Magnetic materials are seldom used in powder form, nearly all the output being utilised as solid cores after pressing, moulding or sintering. Apart from the need for a stable material available in solid form, the permeability of a loose magnetic powder is much too low for practical purposes, and the reason for this is apparent by consideration of the equivalent magnetic circuit of solid metal with an air-gap representing the space between the particles in the direction of the flux. Since the pack density of a low-loss powder (i.e. gross volume/weight) is generally of the order of half the density of the solid metal in the particles, about half the volume of the magnetic circuit is air and so the combined permeability of magnetic powder and space approaches the permeability value of air, namely unity.

In practice, it is usual to insulate the magnetic powder by coating all the particles with a very thin film of plastic or ceramic material and then to press the insulated powder to the required final shape in a mould at high pressure. The insulation serves primarily as a means of reducing eddy current losses and sometimes also acts as a binder, although the pressure intensity is so great that the particles distort and interlock to give a mechanically strong structure. As will be described later, the insulation process must withstand the subsequent heat treatment of the cores necessary to relieve strain.

It is convenient for permeability calculations to consider the pressed and insulated powder core as approximately equivalent to a core of equal

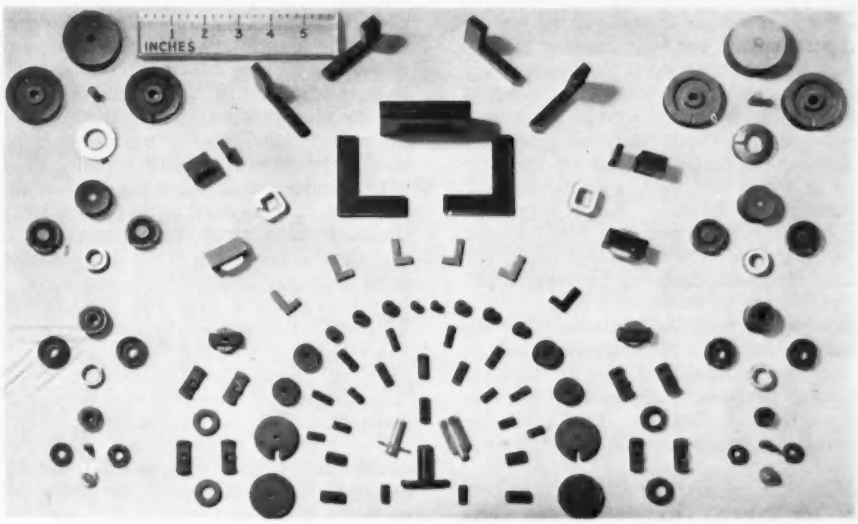


Fig. 3.—Various types of radio cores.

section but with a small radial air gap with parallel sides such that

$$\frac{\text{gap volume}}{\text{core volume}} = x$$

If μ_m = permeability of solid metal

μ_c = combined permeability of core and gap

Then by the calculations of magnetic reluctance for core and gap

$$\frac{1}{\mu_c} = \frac{1}{\mu_m} + x$$

since the permeability of the magnetic metal will generally be greater than 1,000, the term $\frac{1}{\mu_m}$ can be neglected for a first approximation and

$$\mu_c \simeq \frac{1}{x}$$

Hence the effective core permeability is approximately inversely proportional to the equivalent air-gap volume as a percentage of core volume. This means that in practice the maximum permeability of insulated powder cores is between 100-500 and the insulation film is extremely thin (of the order of 0·001 mm. or 0·00004 in.) but sufficient to insulate the cores in order to reduce the eddy currents to negligible proportions at power frequencies. For higher frequency uses the eddy current losses can be further reduced by adding a greater percentage of insulation which increases the film thickness and reduces the permeability so that a balance can be maintained between the iron and copper losses.

In comparison with the solid metal or stampings there is a great reduction in the permeability of a magnetic metal or alloy when it is produced in the form of an insulated powder core, but this disadvantage is counterbalanced by a very great improvement in the stability of the core with time or when subjected to magnetisation. On account of these advantages, magnetic powder cores are particularly suitable, especially in the form of a ring core with no leakage field, for use as inductance standards or for component parts for measurement purposes.

The required properties of magnetic powders to meet the diverse needs of the electrical industry may now be summarised as follows :

(*a*) Physical properties of uniform particle shape, high density and ductility to be suitable for insulation and pressing processes.

(*b*) appropriate particle size and size distribution for the wide variety of cores from power to radio frequencies.

(*c*) availability of powders of the various metals and alloys described in section 2 above.

(*d*) adequate chemical purity to give high permeability and low losses in the core material.

4. PRODUCTION OF MAGNETIC POWDERS.

There are four principal methods in use in different parts of the world for the manufacture of various grades of iron and iron alloy powders. These are briefly described with comments on the advantages and applications of each process :

(*a*) Electrolytic Process.

The first iron powder used for the manufacture of magnetic powder cores was made by the Western Electric Company in America in 1915 by the electrolysis of a solution containing ferrous sulphate and chloride and ammonium sulphate using anodes of mild steel and cathodes of polished sheet steel. The material was obtained in brittle sheets of about $\frac{1}{4}$ in. thick which were broken down by mechanical methods. The powder was subsequently heat treated, insulated with shellac and moulded at high pressure into thin circular rings, with maximum permeability of 35, for use as loading coils for telephone cables. This process was replaced by the method described below for making nickel-iron alloy powder cores.

The principal advantage of electrolytic iron powder is that it is brittle and so can be ground by mechanical methods to the requisite fineness, whereas most other low-loss magnetic metals are ductile and so are very difficult to produce in the form of powder unless special methods are employed. There is a considerable production of pure iron powder by electrolytic methods in this country for a variety of applications.

(*b*) Mechanical Disintegration.

Iron filings, as traditionally used in mapping the field of a permanent magnet, are probably the most widely known form of mechanically disintegrated iron. Modern processes employ ball-mills to grind down brittle cast metal to the requisite fineness and the required powder fractions are separated by sifting, the oversize material being returned to the mill for further grinding. Low grade iron powder is made by this method but the percentage of impurities is generally too high for most magnetic applications.

The high grade nickel-iron alloys are very ductile and cannot be ground by mechanical disintegration in the form in which they are generally used in the electrical industry. A method was developed in America of melting

the constituent metal elements in a high frequency furnace with an embrittling agent such as sulphur, making it possible to break down the cast material to small pieces which can be fed into a ballmill. This is the principal method now employed in the United States for the manufacture of the large quantities of nickel-iron alloy powder cores required for loading coils and carrier frequency filter coils. There are limitations to the fineness to which the powder can be ground by this method so it does not appear to have been used for preparing powder used in high-frequency cores.

The Hametag Process or Eddy Mill is a method used in Germany on a considerable scale for the production from chopped wire of metal powders of smooth and regular shape. The small pieces of wire are fed into opposite ends of a closed chamber through revolving propellers and are ground together by attrition to fine powder. This process is used principally for making iron powders for the production of mechanical parts by powder metallurgy methods, and so far has found only limited applications for the electrical industry.

(c) Carbonyl.

Chemically reduced iron when treated with carbon monoxide under pressure produces iron pentacarbonyl in liquid form. This is decomposed in a heated chamber and deposits fine iron powder with unusual properties, the particles being spherical and mechanically very hard. Although this is usually a sign that the material will have high hysteresis loss, this carbonyl iron powder makes magnetic cores with very low hysteresis and eddy current losses, but the permeability is very low. Hence the principal use for this powder is in the production of a variety of high-frequency magnetic cores, principally for the radio industry. This process was originally developed for the manufacture of nickel in pellet form, but it was also developed in Germany for the manufacture of iron powder. Large quantities were made and exported for the manufacture of cores for radio and telephone applications, but in the second World War plants were also installed in Great Britain and U.S.A. which now produce some thousands of tons annually. The hard fine carbonyl iron powder can be heat-treated to give a softer powder which will press into cores of higher permeability, but at the expense of hysteresis losses. In this form the magnetic quality of the material is similar to that of iron powders made by other methods.

(d) Chemical Reduction.

The chemical reduction of oxides or other compounds in hydrogen at high temperatures has been known for many years for the production of iron powder, described as ferrum reductum for various chemical uses. The application of this process for the manufacture of magnetic powders was at first not successful because the quality of the product was inferior to that of electrolytic iron powder in several ways. However, this reduction process was examined in detail at the G.E.C. Research Laboratories about 25 years ago and tests were made on the reduction of pure iron oxides and the mixed compounds of nickel and iron for the production of high grade alloys. By the addition of successive heat treatments and mechanical processes described in the next paragraph, it was found that satisfactory magnetic powders could be produced on a laboratory scale and this method was then developed on a commercial basis for the production of nickel-iron alloy powders ; it was later extended to the manufacture of pure iron powder and various alloy powders in a number of particle size gradings.

A chemical reduction process is used in Sweden to produce from their very high-grade natural iron oxides a low-cost iron powder known as " Swedish Sponge Iron ". This is widely used in powder metallurgy processes, especially in the United States which has imported some thousands of tons annually, and has now arranged to produce it in quantity.

The process used in the Heywood Works produces both pure iron and nickel-iron alloy powders in coarse, medium and fine particle sizes, and in these respects it has the advantage of flexibility in comparison with other methods, each of which has specialised application generally for one type of powder. The technical background of this chemical reduction process is described in the next section and is followed by a description of the plant and manufacturing process.

5. Chemical Reduction Methods.

It is a well-known chemical process to pass hydrogen, or other reduction reducing gas over iron oxide heated at temperatures about 500

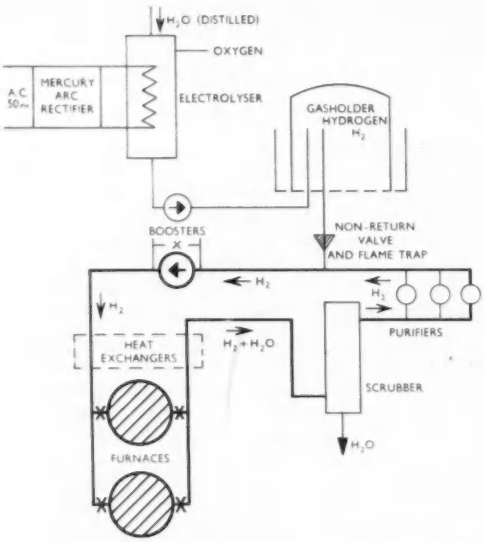


Fig. 4.—Simplified diagram of hydrogen reduction plant.

degs. C. in order to produce a soft and spongy iron powder. The fineness and purity of the reduced iron powder are dependent upon the particle size of the oxides, the impurities present and the temperature and time of reduction.

If the iron powder is very fine and irregular it will oxidise rapidly on removal from the furnace with the generation of such heat that its temperature may be raised from cold to red heat in a few seconds, the material reverting to iron oxide. This type of powder is known as pyrophoric iron.

At first the considerable technical experience already available on the production of tungsten and molybdenum powders was applied to the reduction of pure iron powder for magnetic cores, but the hysteresis loss was high and the permeability too low for practical purposes. Experiments were therefore made in the reduction of intimately mixed oxides of nickel and iron obtained by a co-precipitation process in order to produce a metal powder in which all the particles were complete homogeneous alloys of 80/20 nickel-iron composition. This was successful, apart from initial difficulties in grinding the material to fine powder, and the process was later simplified by mixing specially prepared oxides in the dry state.

In these processes it was found that the powder produced by chemical reduction alone was unsuitable for making insulated powder cores because the porosity of the particles caused the insulating film to break down during the subsequent pressing operation. An important part of the development programme was therefore directed towards grinding, heat-treating and processing the reduced powder to convert the particles to the requisite degrees of smoothness and regularity of surface and to impart a high particle and powder density. As a result of this work it was possible to devise manufacturing schedules for the production of powders of pure iron, silicon-iron and nickel-iron alloys with properties suitable for insulation and for pressing into cores with high specific resistance and excellent magnetic quality.

6. PRODUCTION PLANT.

The design and operation of a process to make magnetic powders on a production scale by

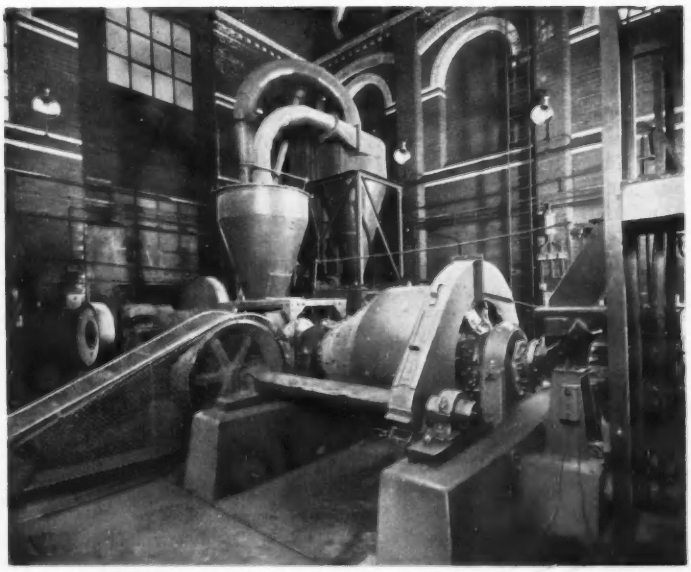


Fig. 5.—Conical ballmill for preliminary grinding and separation of magnetic powder.

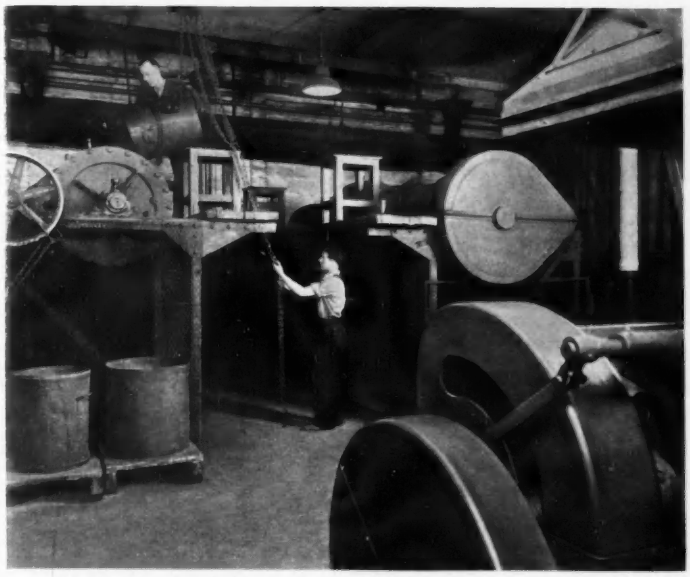


Fig. 6.—Barrel mills for grinding and finishing the magnetic powder.

chemical reduction in hydrogen involves special plant, control equipment and handling methods, together with protection against fire and explosion hazards from both the powder and the hydrogen at elevated temperatures.

The reduction of oxides was originally carried out in a series of horizontal tubular furnaces in which the hydrogen entered at the closed end and metal " boats " containing the material were fed through the open end at measured intervals of time dependent on the required size range of the final powder. The hydrogen was burned at the open end as a precaution against explosions. Pure dry electrolytic hydrogen was used and the rate of flow and temperature gradient of the furnace were accurately controlled. This process was used successfully for some years in the manufacture of high-grade powder but was somewhat uneconomic and unsuitable for the production of several tons per month, and so a reduction method was developed using the G.E.C. vertical cylindrical furnace on a closed gas cycle. It was found necessary to associate this with complete equipment for circulating, purifying and cleaning the gas, removing all the steam produced by the reduction process and equalising the temperature difference between inlet and outlet to the furnace by a system of heat exchangers.

(*a*) REDUCTION.

The chemical reduction plant is shown diagrammatically in fig. 4, all the control equipment and safety devices being omitted in the diagram for simplicity. Because of the necessity for high purity in all materials and processes, electrolytic hydrogen of 99·9 per cent purity is used and is generated adjacent to the plant on a considerable scale. A large Witton mercury arc rectifier plant supplies current up to 2,000 amps. through a series of electrolytic cells containing caustic soda to which distilled water is continuously supplied. The water is split up into its constituent gases and both the hydrogen and oxygen are collected, cleaned and stored in gasholders, the oxygen being used for other purposes.

The hydrogen from the outlet to the gasholders is connected to the closed gas circuit into which it automatically flows as the reduction proceeds, and as the steam resulting from the reduction is condensed. The hydrogen booster maintains adequate pressure to drive the hydrogen through the charge in the furnace, around the condensing and purifying equipment where gaseous impurities are removed, and back to the furnace through the heat exchangers. In this way a continuous flow of high purity hydrogen is supplied to the furnace with very little wastage and the rate of reduction is such that a quarter ton charge can be reduced in a few hours.

The chemical charge is packed in specially made circular trays so that there is a radial flow of gas of uniform velocity throughout the charge. Ultimate physical properties of the powder are controlled by the rate and extent of reduction, the amount of hydrogen consumed and the temperature cycles, each of which is recorded on an appropriate instrument housed in a control room adjacent to the furnace shop. For the production of alloy powders, special mixing and blending machinery is used to prepare the oxides in their correct proportions before charging them in the furnace.

The vertical cylindrical furnace consists of a series of sealed pots of heat-resisting

alloy which can be slung by a crane into the heated zone during the reduction of heat treatment and removed into cooling pits when the heating is completed. The furnace is installed below the floor of the furnace shop to give additional heat insulation and also to facilitate the connection of the pipes and thermocouples during the frequent movement of the pots from furnace to cooling pits and back after emptying and re-charging (fig. 1). This plant operates at temperatures from 600 degs. C. to 1,000 degs. C. and is used for both reduction and all subsequent heat treatments of powders.

(*b*) GRINDING.

The problems associated with the grinding of magnetic materials required the development and application of special machinery. The reduced material taken from the furnace is broken up and milled to powder which is returned to the furnace for a sintering process to convert the partial alloy into a homogeneous alloy. During this sintering process the material is removed in the form of solid " cakes " which,

Fig. 8.—Apparatus for particle size distribution measurement.

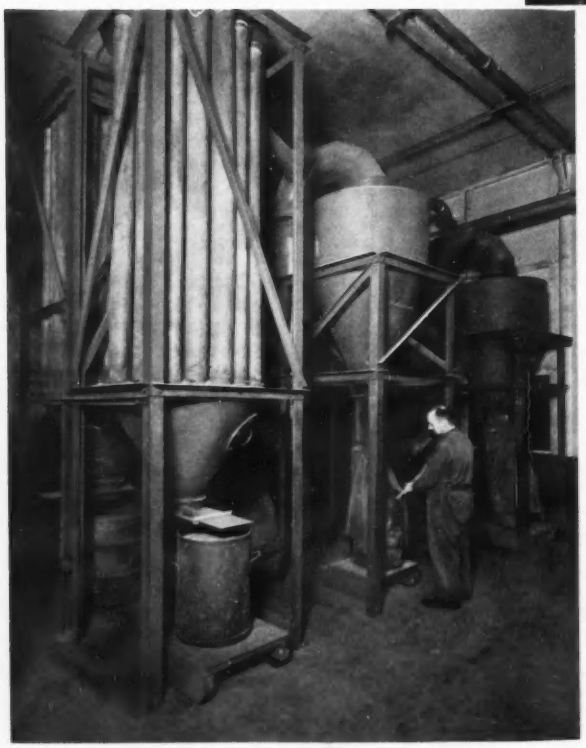


Fig. 7.—Air separation plant.

on account of their porosity, can be broken down again with special equipment although the alloy is basically in a ductile condition. Two types of crusher are used to grind the material down to pieces about $\frac{1}{4}$ in. diameter and these are fed automatically into a conical ballmill coupled to a preliminary air separation and grading plant (fig. 5).

The purpose of this process is not only to grind the powder but to clean it and to impart to each particle a solid mechanical structure. A strong current of air is generated by an external blower and circulated in the ballmill as it rotates, removing the particles below a certain size and density and giving them a preliminary classification. The system used automatically returns oversized powder to the mill and ensures complete and efficient grinding within a range of particle size which can be varied by controlling the feed, the rate of grinding and the

speed of removal of the powder from the mill.

The powder is now given a further ballmilling in a cylindrical batch mill in which the ball charge and speed of rotation are so controlled that the powder is made smooth and regular (fig. 6).

(*c*) SIFTING.

Two types of sifting equipment are used : mesh sieves in special sifting machinery for coarse powders down to 300 mesh per inch and air separating plant for finer powders (fig. 7). The characteristics of high particle density and regularity facilitate the handling and separation of the powder at the later stage of the manufacturing process, but it has been necessary to introduce an exactness of separation and grading difficult to obtain with commercial machinery. Hence special adaptations of cyclone separators have been developed, both for production and measurement processes, to provide a range of particle size gradings for all frequencies used in electrical engineering.

For scientific particle size measurement a Haultain " Infrasizer " is used (fig. 8) and all types of powder are separated and tested in ranges from 10 to 200 microns in diameter (1 micron = one millionth of a metre).

(*d*) PURIFICATION.

In order that the process for making alloy powders by chemical reduction methods shall operate satisfactorily, careful attention is given to the purity of the materials at each stage. It is generally necessary, however, to add a subsequent purification process to the powder at an intermediate stage before the sintering process in order that traces of impurities can be eliminated.

This is carried out in practice by the use of large tanks in which the powder is mixed with various acids of controlled strength and subsequently filtered and dried.

(*e*) INSULATION.

Although the insulation processes are generally considered as part of the core production, the technical requirements are so closely linked with the powder production that it is appropriate to consider the subject under this heading. The insulation process is primarily to increase the resistivity of the finished cores so that they will operate under alternating current conditions with minimum eddy current loss. In some cases, notably in the use of plastics, the insulating material also acts as a binder to increase the mechanical strength and this applies especially

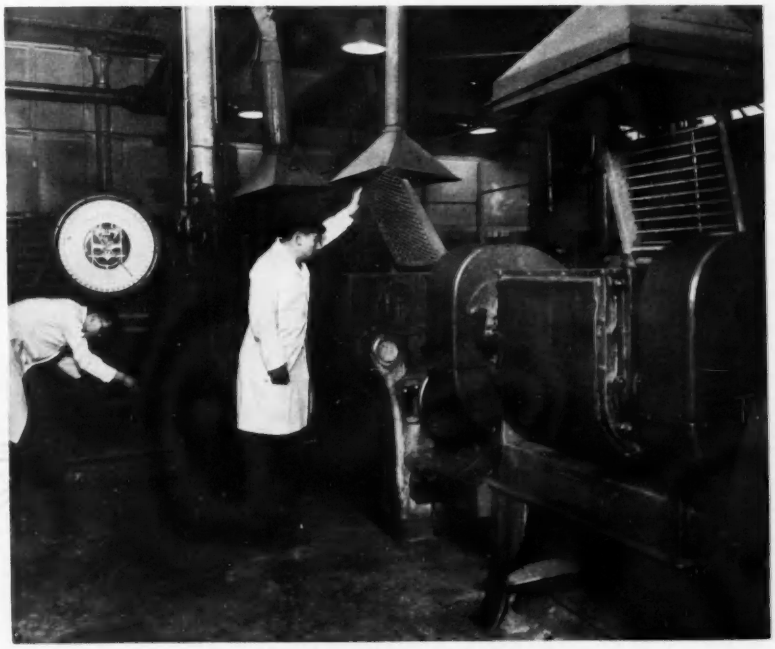


Fig. 9.—Powder mixing and insulating plant.

Fig. 10.—Physical Laboratory.

impart the permanence and mechanical strength which such cores now maintain for indefinite periods of time.

A second type of insulation is required for cores which must be finally heat treated at temperatures in excess of 600 degs. C. in order to remove the mechanical strains in the metal introduced by the high pressures used in the core forming process. This powder insulation process is carried out in various types of special heated mixer using a wet mixture which is gradually evaporated until each particle is coated uniformly (see fig. 9) with a ceramic material.

The plant described above has been in continuous operation for over eleven years and has produced well over 1,000 tons of high-quality magnetic powders of various compositions and grades. Most of this powder has been made into many millions of cores for telephone and radio equipment.

7. TESTING OF POWDERS.

The operation of the process just described can produce high-quality magnetic powders of great uniformity only if the materials are of adequate purity and the production schedules

to low permeability cores for use at radio frequencies. In practice, a core pressed from well-insulated magnetic powder should have a value of specific resistance approaching that of an insulating material, and hence the powder insulating process is in many ways the most critical part of the manufacture of magnetic powder cores.

In the plastic type of insulation the powder is mixed with the requisite amount of insulating material dissolved in a solvent and mixed in a heated paddle mixer until the material is nearly dry. It is then granulated and pressed into cores but the insulating material is not finally polymerised until after the core has been pressed, either in cold or in heated dies, in order to

Fig. 11.—Electrical and Magnetic Laboratory.

are accurately controlled. This calls for a very comprehensive system of chemical, physical and electro-magnetic tests each of which is carried out in a separate works laboratory adjacent to the production plant. It has also been necessary to develop a range of special test equipment, a separate department being engaged in the construction and maintenance of this apparatus.

powder, and hence it is usual to compress the powder into solid blocks or toroidal cores. In most cases the powder is first insulated, which is specially important for cores for use at high frequencies, but the same methods as are used in the case of plastic insulations serve to bind together such materials as magnetic oxides which do not readily adhere when pressed alone.

Fig. 12.—Hydraulic press department.

The Chemical Laboratory is engaged in the analysis of all raw materials and of the partially manufactured powders at each stage of the process. The Physical Laboratory is responsible for the investigation and control of the particle size, shape, distribution, separation, density and flow properties of all types of magnetic powder. The powder is also tested at intermediate stages and special equipment is used for the measurement of pack density, particle size distribution and powder surface area. A considerable proportion of the work of this laboratory is directed to the control and preparation of the various powder insulation processes (fig. 10).

The final products are mainly judged by their magnetic or electrical properties, so the ultimate test for the powder material consists of measuring the permeability, eddy current and hysteresis losses in the Electrical Laboratory. As indicated in section 2, it is difficult to measure the properties of any magnetic material in the form of a

Low-loss materials are tested, in the form of wound toroidal cores, on A.C. bridges at a number of fixed frequencies within the range of operation of the final product. If these materials are to be used at high flux densities the measurements include the magnetisation curve in addition to loss tests at various flux densities. For permanent magnet materials the properties of remanence, coercive force and the energy content (BH_{max}), are measured on rectangular bar specimens and this does not involve the complication and delay of toroidal winding and testing (fig. 11).

8. CORE PRODUCTION.

The insulated powder is pressed into cores at pressures varying from 20 to 100 tons per sq. in., the great pressures being necessary for higher permeability cores in order that the elastic limit of the metal in the powder shall be exceeded. This increases the density of the pow-

der core to a value approaching that of the solid metal, which is very necessary in accordance with the factors described in section 3, and causes the particles to interlock and makes a core of considerable mechanical strength. The thickness of the insulation is extremely small (a fraction of one micron), but it has to be very strong to withstand this severe pressing process.

The moulding tools, which are made from high-grade steels to withstand these great pressures, are produced in considerable numbers for the wide diversity of cores now being manufactured. The majority of cores so far made have been toroidal or ring-shaped because these give minimum magnetic leakage or cross-talk in telephone circuits, but improved designs of tools have been developed for pressing more complex shapes at high pressures in order that the technical advantages of powder cores can be made available for low-frequency uses. These higher permeability cores are pressed in large hydraulic presses as shown in fig. 12, and tested in special equipment designed solely for this purpose (fig. 13).

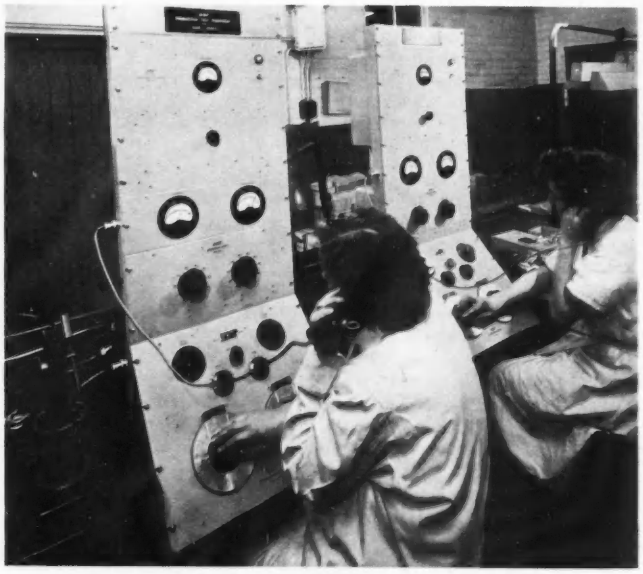


Fig. 13.—Toroid core test equipment.

Radio frequency cores have low permeability and high resistivity values of many megohms and these can therefore be pressed at considerably lower pressure intensities. These pressures are more in the region of those used in powder metallurgy and produce a greater variety of core shapes using automatic presses and pelleting machines. Moreover, the low permeability cores can be made from iron powder in which the purity requirements are not so exacting and the high-quality alloy powders are thus of less importance in this field.

Fig. 3 shows a variety of these radio products in the form of cylinders, EI cores, L cores, iron-clad or pot cores, all of which may be used for coils of fixed inductance value. For variable or adjustable inductance coils the cylindrical cores are moulded together with screwed brass stems, or alternatively an accurate screw thread may be ground by automatic methods along the surface of the core. These are tested electrically by methods shown in fig. 14.

Recent developments have produced high-permeability iron powder cores in a variety of shapes suitable for power applications at the lower frequencies. These are made in some of the shapes described above for radio cores but in larger sizes and also have the important advantages of lower losses, reduced noise under A.C. conditions, and greater magnetic stability in comparison with the stamping cores now used in quantities for nearly all types of power engineering equipment.

9. POWDER MAGNETS.

A very new development, the result of important scientific and technical investigations in France during and since the last war, is the production of permanent magnets from extremely fine powders of iron or certain iron-alloys. For this purpose it is necessary to make the powder with a uniform crystal size less than one hundredth that of the particle diameters of the finer radio powders. It has already been mentioned that fine iron powders are pyrophoric, and these permanent magnet powders are extremely active in this respect, necessitating special methods of handling. These difficulties have, however, been solved on a production scale and these fine powders can now be moulded into magnets by methods similar to those described for low-loss cores. Magnets made in

this way have been found to possess the same degree of mechanical stability as the low-loss cores, and to retain their magnetic properties in accordance with the requirements for permanent magnets.

One of the most interesting features of this new development is that, for the first time in history, permanent magnets can be made from pure iron powder and this is of considerable importance in dealing with the present severe shortages of non-ferrous metals, particularly nickel and cobalt. These iron powder magnets give an energy factor similar to that of the best cobalt steels, but with about half the physical density. They also provide a number of practical and constructional advantages over existing steel magnets such as the moulding to exact size without grinding and the incorporation of inserts and pole pieces in the moulding process. It is also possible to produce powder magnets from the same material with a wide range of permeability values, either with high remanence or with high coercive force, which is not possible with present commercial magnets. These micropowder magnets are made by chemical methods very similar to those already described for low-loss powders and a plant for making them under licence in quantities is now being installed.

10. NEW MAGNETIC POWDERS.

The recent restrictions in the supply of nickel and nickel compounds and the increasing demands for powder cores of all types has focused attention on alternative magnetic materials, of which the most promising is iron. Although experimentally very pure iron has given lowest losses and highest permeability of any magnetic material, at the present stage of development the nickel-iron alloys give appreciably better performance at low flux densities, especially for cores used at telephone transmission frequencies. Therefore attention has been directed to the economy of use of nickel by improving the properties of its alloys, as well as to the use of pure iron as a substitute where lower quality can be tolerated.

During the last two years a new ternary alloy powder of the copper-nickel-iron series, known as Gecalloy III, has been developed and is now in quantity production. Cores made from this powder have higher permeability and lower losses in comparison with any of the other alloys now being manufactured, and these improvements have been employed in reducing the size of the core while maintaining the electrical performance. For most of the cores used for telephony the size reduction has been nearly 50 per cent and this has also resulted in a similar reduction in the amount of copper wire used. Thus, even with a reduced allocation of supplies of both nickel and copper, it has been possible to increase the output of telephone coils considerably, with the added advantages of reduction of the space occupied by them in loading coil manholes and in telephone equipment.

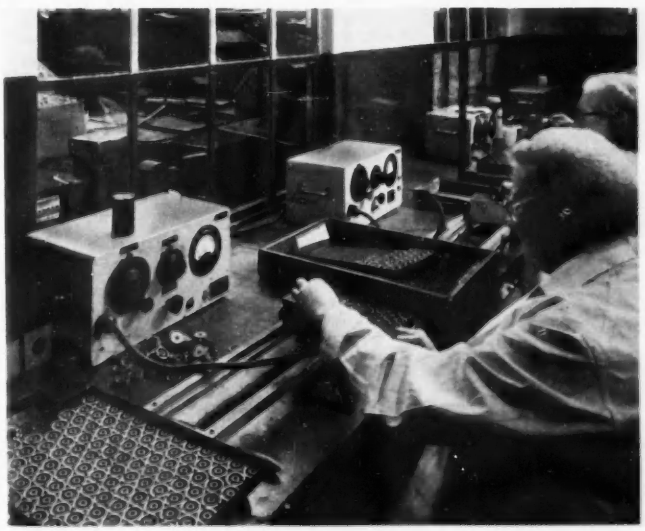


Fig. 14.—Radio core test equipment.

A new grade of iron powder for low flux densities use (Gecalloy RX) has been developed and is now applied for making iron powder cores as substitutes for the alloy cores for various telecommunications uses. Toroidal cores made with this material give better performance than any of the former higher permeability grades of iron powder cores hitherto used for these purposes, but the cores must be somewhat larger than any of the nickel-iron cores to obtain the same electrical results. A comparison of the performance curves of the two materials at frequencies up to 10 kc/s is given in fig. 15.

Another iron powder (Gecalloy PL) for powder appli-

cation now being manufactured combines adequate permeability and low hysteresis at high flux density with magnetic saturation approaching that of pure iron. The permeability range of cores made from this powder is higher than that of any of the telecommunications cores, but the eddy current losses at the lower power frequencies (50 cycles/sec.) are almost negligible. The total losses under these conditions are somewhat lower than those of the silicon steel stampings used in quantities in most electrical machinery and power equipment. However, the permeability of the powder cores is much lower than that of the stamping cores and so the new material cannot be used as a substitute in an existing product. Nevertheless, it has many applications at these frequencies where much greater magnetic stability is required. At higher power frequencies such as 400 and 850 cycles/sec. used in mobile equipments for vehicles and aircraft, the much lower A.C. losses of the powder core give it a decided advantage.

As a result of the production of these new powders, manufacture of other nickel-iron powders has been discontinued. Silicon-iron powder was made in the last war as a substitute for German carbonyl-iron powder, but the latest pure iron powders described above give better performance. A 50/50 nickel-iron alloy powder (Gecalloy N) has been in production for several years to provide a fine high permeability low-loss material for radio cores and also a coarser powder for power applications. Cores for the latter use approached the quality of the 80/20 alloys regarding losses and permeability values, but had the advantage of higher saturation flux density and lower cost. This applies also to the new pure iron powder cores, but the losses at high flux density are somewhat greater than for either of these nickel-iron alloys.

With the great advance in magnetic tape recording since the last war, there has been an increasing demand for very fine magnetic iron oxide with a particle size of the order of one micron. This powder with permanent magnetic properties has the advantage that when dispersed in suitable liquids, it can be spread on to a plastic tape or band which will then serve as a high-quality magnetic recording medium. This material is now being made in the plant described above by heat-treating iron compounds in controlled gases in order to convert them to magnetic oxides with the desired properties and particle size range. Permanent magnets can be made by mixing this material with a binder and pressing into solid blocks, but the properties are inferior to those of metal micro-powder magnets described in section 9.

11. COMPARISON OF MAGNETIC MATERIALS.

Before the advent of magnetic powder cores, transformers and chokes for higher frequencies were wound on non-magnetic materials (air cores) and those for lower frequencies were constructed with assembled stampings of silicon steels. An air core has no hysteresis loss but the D.C. resistance of the windings is excessive and the quality factor is low except at higher radio frequencies. By contrast, the copper losses for cores made with stampings tend to be relatively low, being inversely proportional to the

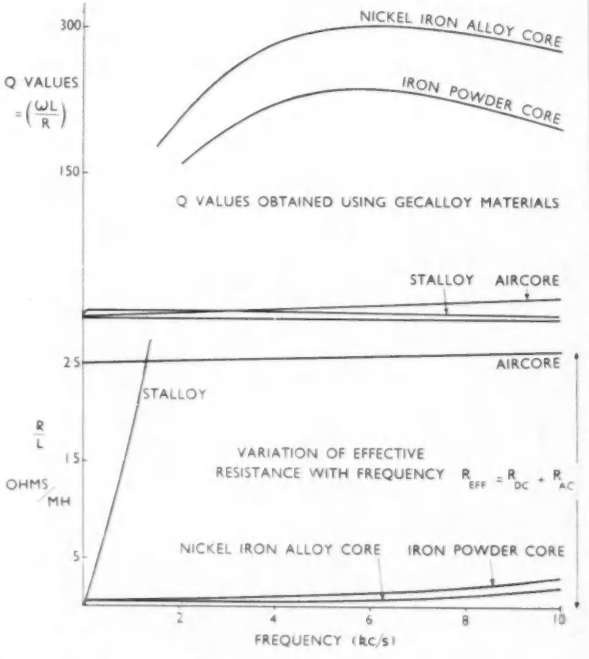


Fig. 15.—Performance curves for powder cores in comparison with other magnetic cores.

permeability at the lowest frequencies, but rise rapidly with increase of frequency. These factors are shown in fig. 15 which gives the losses in terms of effective resistance per millihenry and the quality factor $\frac{\omega L}{R}$ (where L is the inductance in henries, ω is $2\pi \times$ frequency and R is the effective resistance in ohms) for the frequency range up to 10 kc/s.

The powder cores in various permeability values, from 10 for highest frequency uses to 100/500 for lower power frequencies, have thus filled an important gap in the requirements for magnetic materials. The chief limitation is that the permeability is not high enough for many applications especially at lower frequencies, but it may be increased further by reduction of the percentage of insulating material, but at the expense of eddy current loss. An alternative method of obtaining this desired increase in permeability is to convert the powder to flakes and to press them with the flat surfaces parallel to the direction of the magnetic flux.

During the last war, new types of non-metallic magnetic materials, known as ferrites, were developed in Holland. These consist of various mixed oxides which are pressed in moulds and sintered at very high temperatures to form hard and brittle cores with similar mechanical properties to ceramic substances. Their chief advantage compared with powder cores lies in their higher permeability values together with high specific resistance, but this is offset by low saturation flux density (about one quarter the value for iron powder cores) which is characteristic of most non-metallic materials. This latter disadvantage tends to make ferrites unsuitable for power uses, and most of the applications appear to have been for telecommunications coils and transformers. At higher frequencies where lower permeability cores are used, the specific resistance of the powder core material approaches that of an insulator and exceeds that of the ferrites ; these have therefore not been used extensively up to the present time for radio cores where eddy current losses are the most important factor affecting quality. Powder cores can be pressed to accurate dimensions without subsequent grinding which is a useful advantage in manufacture.

Both ferrites and insulated powder cores are

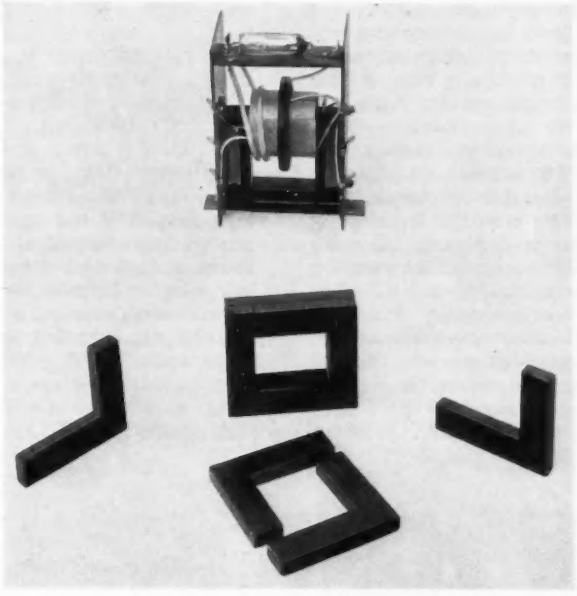


Fig. 16.—Television transformer using powder L-cores.

made by moulding methods which have the advantage that they can be used to press shapes which cannot be made with assembled stampings.

12. APPLICATION.

The applications of magnetic powder are now so numerous that it is not possible to give more than a very brief summary of them here. Although most of the output is for cores for telecommunications, the new developments of powder magnets and high flux density cores will extend the field into various electrical power applications, though principally for smaller components which show the greatest benefits of quantity production.

The output of alloy powder is now mostly used for telephone transmission equipment, principally loading coils for telephone cables or carrier frequency filter coils, the latter being required to combine or separate the many speech channels before and after transmission over long cable circuits (figs. 17 and 2). The cores for these purposes are mostly toroidal or ring-shaped and are wound on special machines to make coils with very high magnetic stability and negligible leakage field, so that large numbers can be assembled in very small space without mutual interference or cross-talk. Quantities of these toroidal alloy cores have also been used for standard inductances and for radio interference suppression. However, iron powder cores can now give improved results for the latter purpose due to their higher saturation flux density, and are much cheaper and free from restrictions of supply.

Powder cores for high frequency uses were first made in Germany 20 years ago from carbonyl iron powder. They are now used in very large quantities for inductance coils in all radio and television equipment so that the total annual consumption of magnetic powder for radio now probably exceeds the amount used for telephone cores. In addition to these low flux density cores, there is now a demand for powder cores for television line time base transformers which are required to operate at high flux density at high frequency and utilise new materials described in section 10. These are made in the form of L-shaped cores, a transformer core consisting of four of these pressings clamped together with overlapping butt joints to ensure minimum leakage flux and greatest efficiency. These cores (fig. 16) are much easier to assemble than the thin stampings formerly used and result in a great reduction of noise.

A smaller type of L-core is made for use in

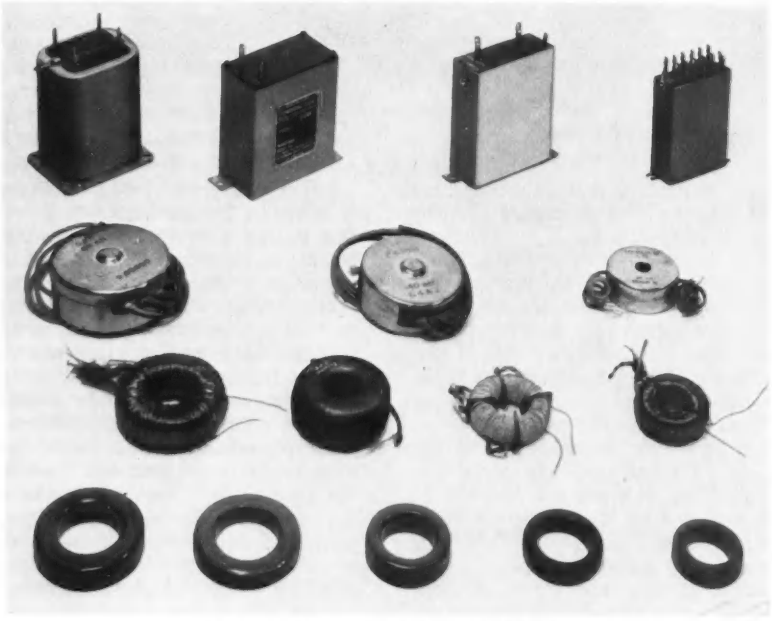


Fig. 17.—Gecalloy III toroidal cores and coils.

Fig. 18.—Electro-mechanical converter instrument.

interference suppression and lighting chokes, and these can be assembled in core stacks which give adequate cooling with efficient use of materials. In the case of chokes to be used either at lower frequencies for general installation and for higher power frequencies for train or aircraft lighting, low acoustic noise is essential and both toroidal cores and assembled L-cores give good performance in this respect.

The new high flux density core materials have important applications for measuring equipment which requires high magnetic stability together with high saturation flux density. An example is the electro-mechanical converter instrument developed by this Company for measuring all kinds of mechanical quantities by electrical instruments. This consists of a converter unit or transducer, magnetised by the A.C. 50 cycle mains supply, which converts a small mechanical displacement into corresponding electrical current to operate an electrical instrument calibrated in the mechanical quantity. The transducer consists of a number of cores of Gecalloy PL assembled together so that the moving core which is displaced by the mechanical movement is located in the centre of the magnetic circuit, thus minimising leakage field (figs. 18 and 19).

There are numerous other applications of both low-loss and permanent magnet powders which are being developed and these materials can be expected, either singly or together, to have considerable influence in the future design of many electro-magnetic products.

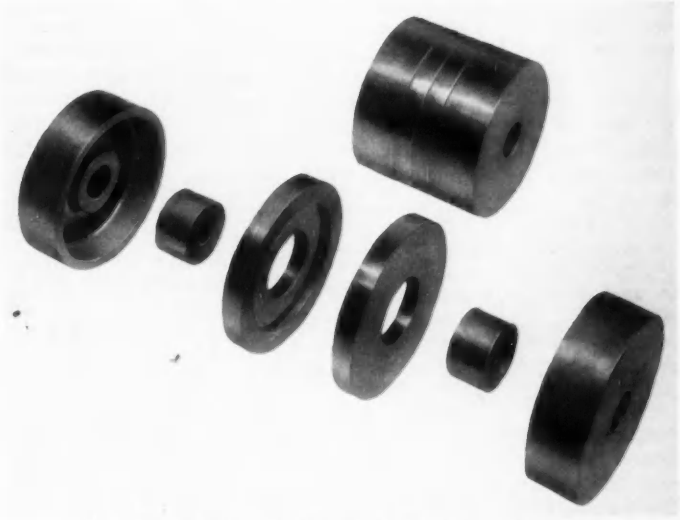


Fig. 19.—Cores for electro-mechanical converter instrument.

Supervisory Equipment for the Indication of Shaft Distortion in Steam Turbines

By D. ANTRICH, B.Sc.(Eng.), R. K. HILTON, B.Sc.(Eng.), and H. W. B. GARDINER, B.Sc.(Eng.), M.I.E.E.
G.E.C. Research Laboratories.

New equipment has been developed in order to measure the distortions which the shaft of a turbine may undergo. Owing to differential expansion the shaft may move axially with respect to the casing, also the mean position of the shaft centre in its bearings may change, thus causing vertical and horizontal displacements. In addition, the shaft may bend and rotate eccentrically. All measurements are made electromagnetically on a disc machined integral with the shaft and are indicated and recorded continuously. An additional unit to indicate and record the speed of the turbine is described. Similar equipment could be used for detecting alternator shaft distortions.

INTRODUCTION.

THE trend in the development of steam turbine plant has been towards the use of larger units working at higher steam pressures and temperatures, enabling higher efficiencies to be attained. Many problems have arisen or become of increasing importance due to these operating conditions, some of them being associated with the relative displacements and distortions of the turbine rotor and its casing.

When steam is applied to a turbine preparatory to starting up, the rotor, having less weight and heat capacity than the casing, heats up more quickly. This causes the shaft to expand with respect to the casing, and care must be taken to see that the motion so caused does not exceed the clearances allowed at various points within the turbine. Similar movements take place when there is any sudden change of load or when the machine is shut down, and similar precautions must be taken.

Also, if during starting there is unequal application of heat around the rotor, the resulting unequal expansions tend to bend the shaft slightly, causing those parts of the rotor not adjacent to the bearings to rotate eccentrically. This sets up out-of-balance forces which tend to increase the distortion of the shaft and, if due care is not exercised, it is possible for the eccentricity of motion to exceed radial clearances, so that rubbing and consequent damage may ensue.

To reduce these dangers, it is customary to start the turbine according to a time schedule long enough to ensure fairly uniform heating, thus avoiding the possibility of clearances being reduced below those allowable for safe operation. It is likely that this period could be shortened if precise knowledge were continuously available of the relative displacements in the turbine. With this information plant would be more readily available, particularly at critical load periods.

Similarly, the record of the shaft movement correlated with rotational speed throughout the life of the turbine would enable any progressive deterioration to be detected and permit subsequent analysis of machine performance.

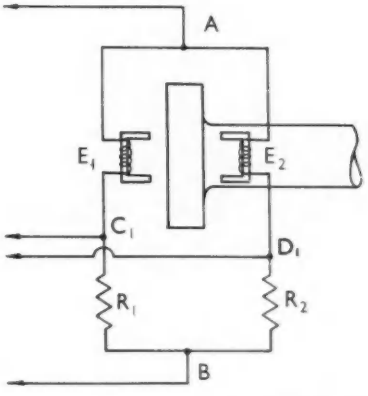


Fig. 1.—Bridge circuit for axial detection.

INSTRUMENTATION REQUIREMENTS.

To meet the above conditions, equipment was requested which would indicate and record three quantities :

(*a*) Expansion of turbine rotor with respect to the casing.

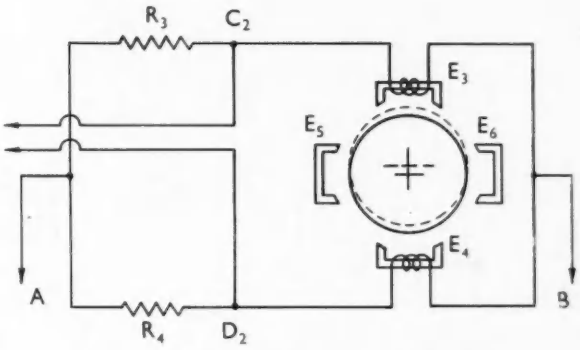


Fig. 2.—Bridge circuit for eccentricity detection.

(*b*) Vertical eccentricity of shaft with respect to the bearing housing.

(*c*) Horizontal eccentricity of shaft with respect to the bearing housing.

The equipment was specified to be independent of normal variations of voltage or frequency of the electric supply, and to have a degree of reliability of the same order as the turbine set itself.

When this equipment was developed it was found possible to give, in addition to the above measurements, values of the mean position of the shaft with respect to the bearing housing, in both vertical and horizontal directions. Thus the position of the shaft journal with respect to the bearing and its oil film could be determined.

Also an auxiliary instrument has been developed, for occasional use during special technical investigations, which displays to an enlarged scale on the screen of a cathode ray oscilloscope, a polar diagram of the motion of the end of the shaft.

To comply with requirements for robustness, thermionic valves are not used in any part of the main equipment. They are, however, used in the auxiliary oscilloscope.

PRINCIPLES OF MEASUREMENT.

In the diagram of fig. 4 the turbine shaft in the high pressure casing is shown supported in journal bearings *A* and *B*, and located longitudinally by the thrust bearing *C*. On the end of the shaft remote from the thrust bearing is a steel disc, *D*. If the shaft expands, the disc moves axially, and if the shaft bends, the disc rotates eccentrically since it is overhung from the bearing.

The position of the disc in any particular direction with respect to the casing is determined by two detector coils which are fixed to the casing at opposite ends of the diameter of the disc. They act as inductances and are placed close enough to, but not touching the shaft, so that the disc is part of the magnetic circuit of each coil. The movement of the disc in the direction to be measured causes the inductance of one to be increased due to reduction of its air-gaps, while the other is affected oppositely.

Thus, if in fig. 1, E_1 and E_2 represent the coils for detecting axial motion of the shaft, these form two arms of a bridge circuit with resistances R_1, R_2 in the other arms. If a voltage is applied to points AB, the state of unbalance of the circuit can be measured at points C_1 D_1.

Similarly, if in fig. 2, E_3 and E_4 represent the coils for detecting eccentricity in a vertical direction, connected to resistances R_3 and R_4,

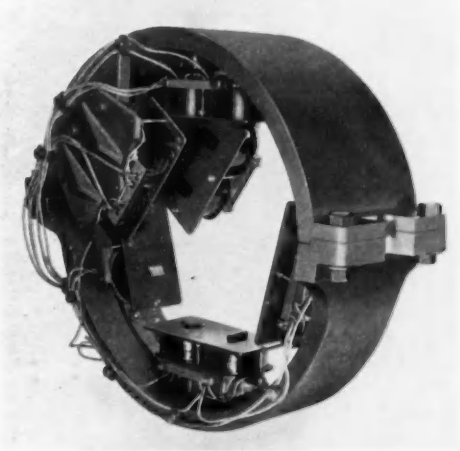


Fig. 3.—Detector coil assembly.

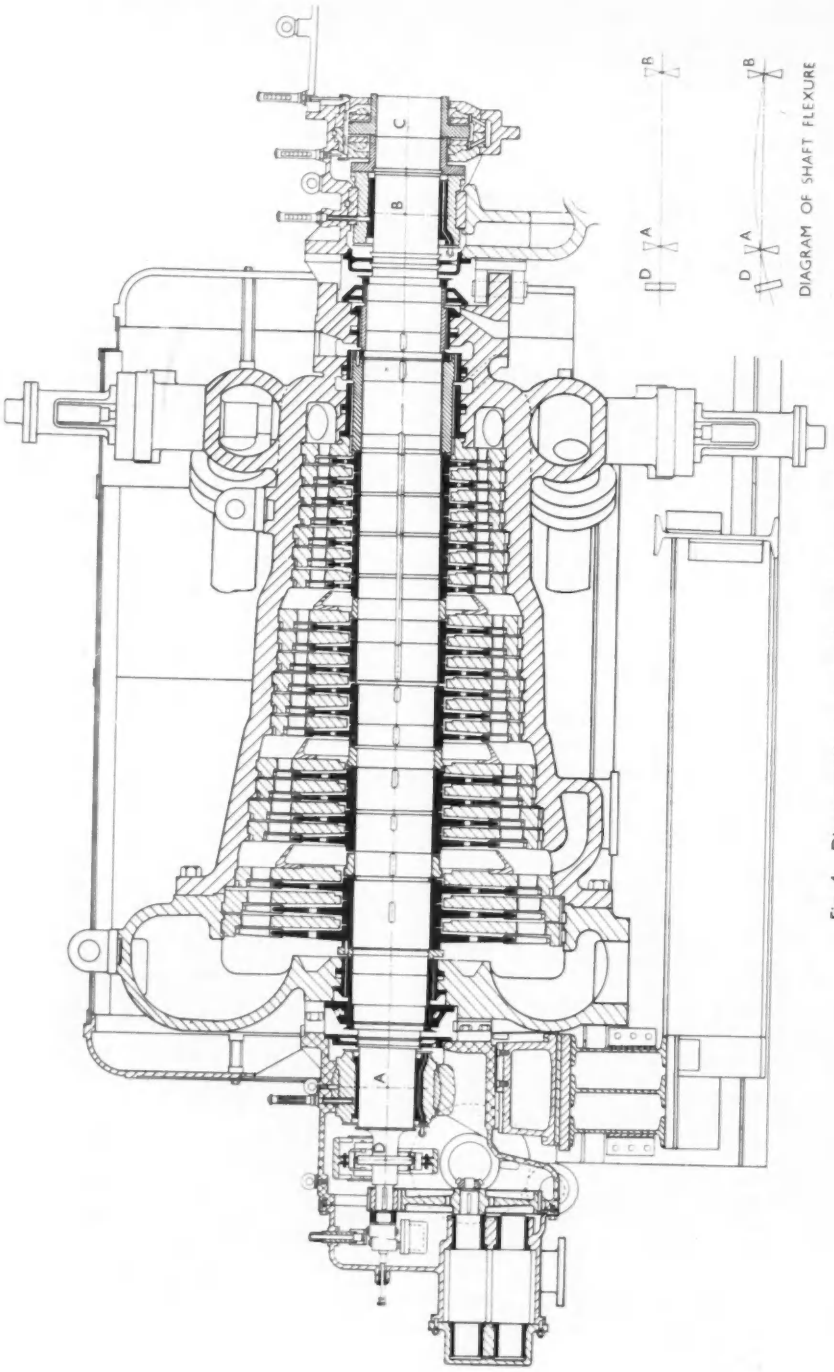


Fig. 4.—Diagrammatic representation of a steam turbine.

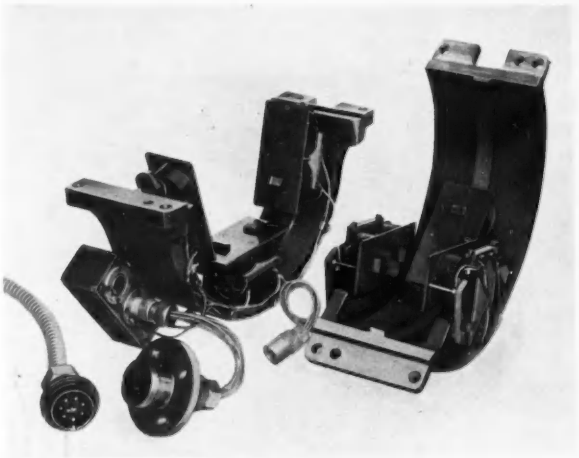


Fig. 5.—Detector coil assembly showing electrical connections.

then any change of vertical position of the shaft will cause a change in the current or voltages at C_2 D_2. Also coils E_5 and E_6 can be connected in a similar circuit for detecting any change of position of the shaft laterally.

The position of these coils in a bronze mounting ring is shown in fig. 3 and 5 and the ring itself is mounted in the turbine bearing housing as in fig. 6. The coils for measurement of horizontal eccentricity are placed slightly below the centre line to enable the shaft to be removed without disturbing them; as they are still symmetrical about the vertical centre line, the accuracy of the reading is unaffected.

The bridge circuits are not normally balanced, but are biased so that they always operate on one side of the null position. Thus, in fig. 1 an alternating voltage is applied at AB, and resistances R_1 and R_2 have values such that when the shaft is in its mean position there is an unbalance which produces a voltage across C_1, D_1. If relative expansion or contraction of the shaft takes place, the movement is directly indicated by an increase or decrease in the voltage across C_1, D_1.

Vertical movement of the disc may be caused either by the shaft bending slightly, thus causing the overhung disc to rotate eccentrically, or by the centre of rotation of the shaft in its bearings changing due, for instance, to a change in oil film thickness. If an alternating voltage of suitably high frequency is applied at AB in fig. 2, and the bridge circuit containing E_3, E_4, R_3 and R_4 has a suitable initial out-of-balance, then bending of the shaft will cause modulation

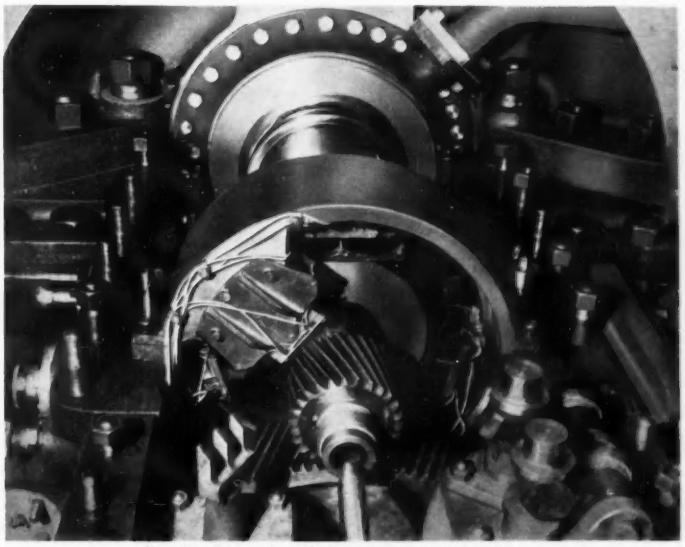


Fig. 6.—Mounting of detector coils in turbine.

of the alternating voltage at C_2, D_2, corresponding to the eccentricity of the disc, and independent of shaft speed. Any vertical change in position of the centre of rotation will affect the mean value of this alternating voltage, but not its modulation. These two quantities are separated and measured on independent instruments.

SOURCE OF SUPPLY.

Since the eccentricity component is cyclic, of period equal to the speed of rotation (in this case 3,000 r.p.m. or 50 c.p.s.) it is necessary, in order to separate the modulation from the carrier frequency, to have an A.C. supply to the circuits of at least 20 times the periodicity of the value to be measured.

Any form of A.C. generator could be employed, the two obvious ones being either a valve oscillator or a rotary machine. Since the equipment is required to operate in a power station, robustness and reliability are essential; and therefore an inductor type alternator has been chosen.

The carrier frequency adopted is approximately 1,000 c.p.s., which is sufficiently high for satisfactory operation of the circuits, and easily attainable with an inductor type machine.

This inductor generator, shown in fig. 7, is driven by an induction motor from the 50 c.p.s. mains of the station, and any variation in this frequency would cause a similar variation in the frequency and voltage of the 1,000 c.p.s. output. To enable the equipment to function accurately

Fig. 8.—Indicating and recording instruments and controls.

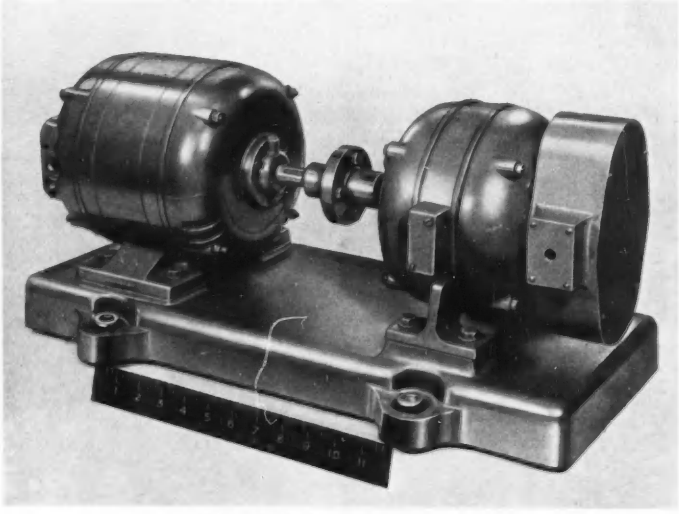


Fig. 7.—High-frequency alternator set.

within the range of such variations, the signals from the bridge circuits are not measured absolutely, but are connected to ratiometer type instruments. With these instruments the signal is compared with current obtained through a second circuit fed directly from the generator. Thus, any variation of voltage or frequency affects both the measurement and reference circuits to the same extent; and their ratios, and hence the readings of eccentricity and displacement, remain unaffected by such variations.

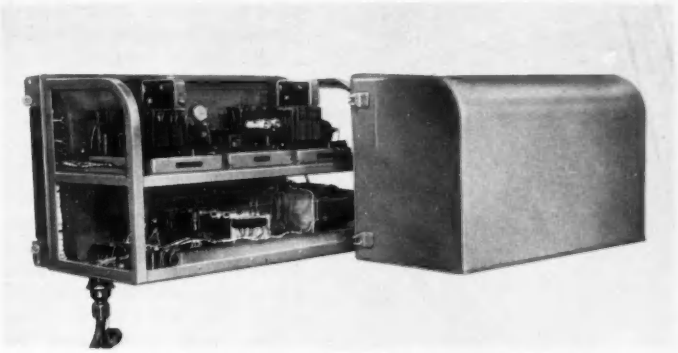


Fig. 9.—Cubicle containing circuit assembly and magnetic amplifiers.

POSITION OF INSTRUMENTS AND EQUIPMENT.

The indicating and recording instruments and controls are mounted on a panel as illustrated in fig. 8, remote from the turbine, but connected to it by an armoured multi-way cable. All the circuit components are housed in a single cubicle fixed to the back of the panel as shown in fig. 9.

PROVISION OF CALIBRATING SIGNALS.

Incorporated in the equipment are means for producing calibration signals for all three circuits, so that the sensitivity of these circuits can be adjusted and maintained to be the same as at the time of initial calibration. The calibration signals for the horizontal and vertical eccentricity circuits are produced by a disc of known eccentricity fitted to the end of the 1,000 c.p.s. alternator shaft. It rotates between two small detector coils mounted diametrically opposite and around the periphery of the disc as illustrated in fig. 10. These detectors are connected in bridge form and simulate the action of the main bridge circuits. The calibration signal for the differential axial expansion is produced by a tapped voltage from the main 1,000 c.p.s. supply. A rotary switch enables the calibration signals to be injected into the three circuits simultaneously.

VISUAL INDICATION OF SHAFT ECCENTRICITY.

When the turbine shaft rotates with constant eccentricity, then the output from the separate horizontal and vertical bridge circuits takes the form of modulated carrier waves, the depth of

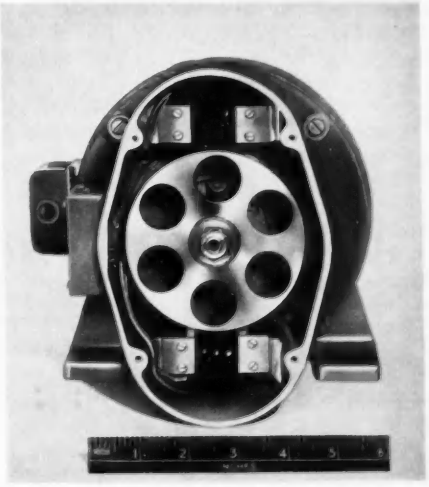


Fig. 10.—Calibrating unit.

modulation being proportional to the eccentricity. These modulated carrier waves, after suitable filtering, appear as two sine waves of

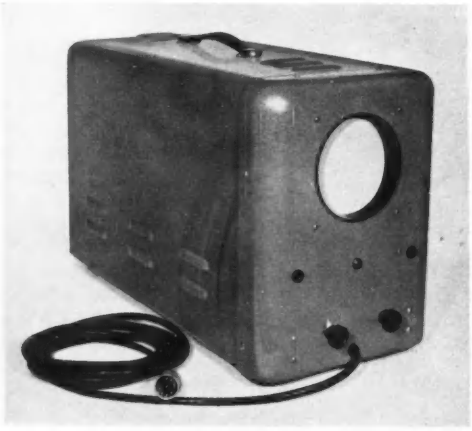


Fig. 11.—Cathode ray oscillograph for tracing locus of shaft centre.

equal amplitude which have a phase difference of 90° due to the physical position of the coils around the turbine shaft.

The two sine waves may be fed to the horizontal and vertical deflecting plates of a specially designed cathode ray oscilloscope, as illustrated in fig. 11. The resulting trace will be circular and representative of the locus of the shaft centre which, in the case of equal signals, will be a circle.

SPEED INDICATOR AND RECORDER.

Additional equipment* has been developed in order to measure and record the speed of the turbine, using a small high-frequency alternator driven from the turbine shaft. As the turbine speed increases from rest, the output from the generator is fed directly to the indicating and recording instruments until a speed of about 2,750 r.p.m. is reached. At speeds above this, the output is automatically switched to tuned circuits before being fed to an indicator and a recording instrument. Two scales are provided on the indicator, the lower is calibrated 0-3,000 r.p.m. for the running-up period, while the upper, for the same scale length, indicates 2,700 r.p.m. to 3,300 r.p.m. The latter scale enables small variations of the rated speed to be detected easily. The recording instrument shows three ranges covering 0-3,000, 2,700-3,300 and 3,200-3,500 r.p.m.

The entire equipment† was developed for installation in each of the six 60 MW turbines for the new generating station of the British Electricity Authority at Uskmouth, Newport, Mon.

The supervisory equipment was installed and connected to the first of these turbines when undergoing steam trials at the works prior to despatch to site. The distortions of the shaft, though small, were easily observed, and a much clearer idea of the relative movements of the various parts was obtained than would have been possible if the supervisory equipment had not been available. All the indications were in general agreement with those expected by the designers of the turbine.

* British Patent Application No. 9532/51.
† British Patent 666/898.

Radiography as an Aid in Research

By A. W. BALLS, B.Sc.
G.E.C. Research Laboratories.

Radiography is well established to-day as one of the most important methods of non-destructive testing. Developments in techniques and the introduction of artificially prepared gamma-ray sources now facilitate the examination of a wide range of articles and materials. At the G.E.C. Research Laboratories a constant check is maintained on the quality of large numbers of experimental samples of articles under development, and assistance is given in many of the problems associated with research and development work.

INTRODUCTION.

SINCE the discovery of X-rays, fifty-five years ago, many beneficial applications of these penetrating radiations have been found in both medicine and industry.

Radiography, or X-ray photography, which has achieved so much in the field of medical diagnosis, has also become one of the most useful methods of non-destructive testing. Although other methods have quite important advantages in particular applications, radiography is of greater general use in that it is more accommodating with regard to such properties of articles under test as shape and material, and is able to provide a permanent visible record of the information which it reveals.

In industry generally, radiography has been well established for many years as a means of examining castings made for a great variety of uses, two of the better known being steel castings for machinery and aluminium castings for aircraft parts. Welds in boilers, pipe lines and ships are also widely checked for possible weaknesses. On a smaller scale packaged goods, particularly foodstuffs, are often subjected to direct visual examination on a fluorescent screen as a precaution against the accidental inclusion of undesirable matter.

At the Research Laboratories the value of X-ray examination has always been recognised and in recent years the demands for such examination have increased to a very considerable extent. This has been due to several factors, one of which is the advances which have taken place in regard to apparatus and technique. Secondly, the introduction of artificially produced radioactive isotopes has enabled thicker and denser materials to be penetrated without elaborate and costly equipment and has also provided an easy and convenient method of performing examinations on site. A third and more local factor is associated with the advances which have taken place in the techniques of joining glass to metal for vacuum seals. A very large proportion of the work at the Laboratories is concerned with vacuum tubes of many kinds, and the large scale changeover from transparent glass bulbs to opaque metal envelopes which has resulted has created an additional field for the use of X-ray examination of experimental samples (fig. 1).

A wide variety of subjects, both vacuum tubes and other articles, regularly present themselves for examination. They can be grouped into three classes:

1. Articles which are being made in experimental or small production quantities and are to be checked for known possible defects or errors at critical stages in manufacture.
2. Experimental articles or components which have failed on test or become defective in use, and require the fault to be identified or located.
3. Articles or apparatus to be examined for determination of condition as an aid to the correlation of their performance with their mechanical state or physical dimensions. In this class no faults or defects are concerned. The method is used purely as an analytical aid to a piece of research or development work.

PENETRATION BY X-RAYS AND GAMMA-RAYS.

The degree to which a material will resist the passage of X-rays or gamma-rays depends on its atomic weight, its thickness and the wavelength of the radiation. A " mass absorption coefficient " can be determined for every element which varies only with the wavelength, becoming less as the wavelength decreases. It follows therefore that the light elements such as aluminium, carbon and magnesium, can be more easily penetrated than iron, nickel or copper, and these more easily than tungsten, gold, mercury or lead. Even in combination their response is the same, the absorption of X-rays in an alloy or chemical compound being in equivalent proportion to the relative quantities of the constituent elements.

For any given wavelength of X-radiation, or voltage of generation, there is a maximum thickness of each element above which it is not practicable to get useful results. In the accompanying Table 1 is given a short list of common elements representative of a range of atomic weights with approximate values of this maximum thickness shown in relation to different energies of radiation.

TABLE 1

MAXIMUM PRACTICAL PENETRABLE THICKNESS IN INCHES.

	100 kV	200 kV	400 kV	1,000 kV
Carbon ...	11	13	17	23
Aluminium ...	8	10	15	20
Iron	1	2·25	4	7
Copper ...	0·65	1·5	3·25	6
Tin	0·25	1	3·25	6
Tungsten ...	0·035	0·1	0·7	2
Lead	0·05	0·15	1	3·5

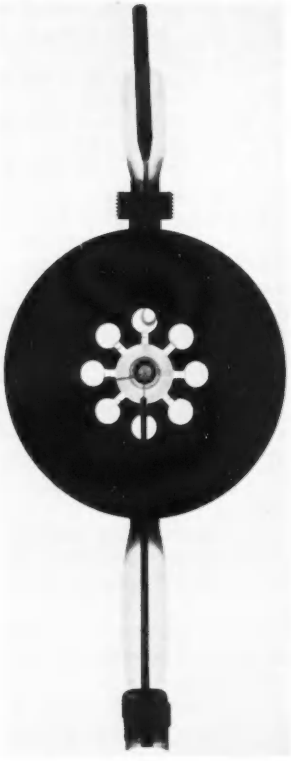


Fig. 1.—X-radiograph of a 10-centimetre cavity magnetron.

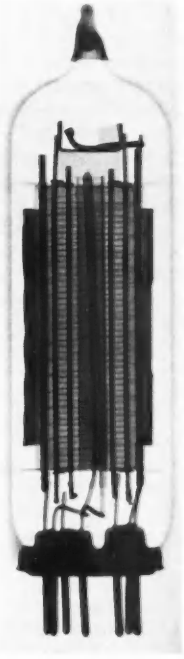


Fig. 2.—X-radiograph of a modern pentode receiving valve. The length is about 2½ inches.

In deciding whether it is possible to achieve a desired result with the facilities available, consideration must be given to the relative absorbing powers of the different constituent parts of an article.

Most of the examinations carried out at the Research Laboratories have been made using a 140 kV X-ray generator supplemented by radioactive iridium and radium gamma-ray sources which have penetrating powers equivalent to about 400 kV and 1,000 kV X-rays respectively.

TECHNIQUES OF RADIOGRAPHY.

The methods of producing X-rays and the design of X-ray tubes will not be discussed here, but mention must be made of one characteristic of X-ray tubes, namely, the focal spot size, which is of great importance in determining the quality of radiographs. As a radiograph is in effect a shadowgraph, the smaller the source of radiation the more sharply defined will be the image. The size of the focal spot on the X-ray tube anode, which is the source of radiation, can be determined in the tube design. For medical work, where it is necessary in dealing with animate subjects to use as great a density of radiation as possible in order to keep exposure time to a minimum, a focal spot of 6 millimetres square is usually employed. A compromise is thus made between length of exposure and image definition obtainable. For industrial work, where longer exposure times can be tolerated, a 2-millimetre square focal spot is commonly used, when at distances from source to subject greater than 2 ft., the image definition is controlled by factors other than the focal spot size.

The sensitivity obtainable in a radiograph varies to some extent with the technique used, and also with the shape and size of the subject. The best generally accepted figure for a sharp discontinuity is 1 per cent. This means that an increase or decrease in thickness of 1 per cent can be seen on a radiograph provided that the change in thickness is in the form of a step and the object is small enough to produce negligible scattered radiation. A more gradual change, as for instance exhibited by a hemispherical hole or a cylindrical superimposed wire, may only permit detection of 2 to 3 per cent changes in thickness. Also, the larger an object, the more likely it is to project secondary scattered radiation on to the film with consequent reduction in sensitivity. For cavities in very large

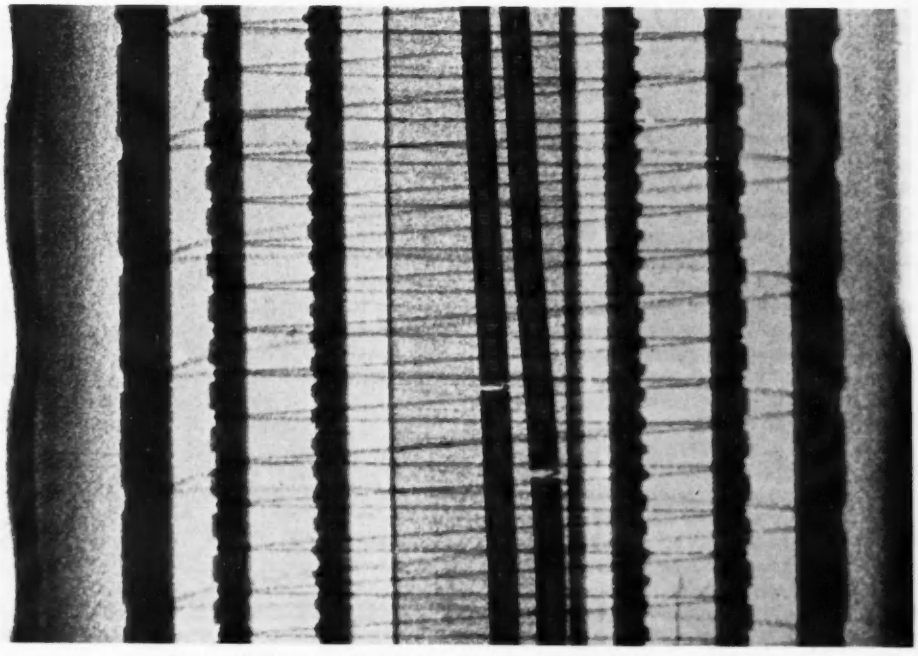


Fig. 3.—Section of radiograph shown in fig. 2. Magnified ten times.

castings a 4 per cent discrimination is considered reasonable. Where superimposed materials of different composition are being examined, the percentages quoted apply to the equivalent absorptive mass of the materials.

The lateral resolution between different parts of an image, for example adjacent wires on a valve grid, is determined to a large extent by the foregoing considerations and, in addition, to such factors as tube focus size and grain size in the photographic emulsion. With suitable subjects and ordinary techniques a discrimination of 0·03 millimetre is quite possible as illustrated by figs. 2 and 3.

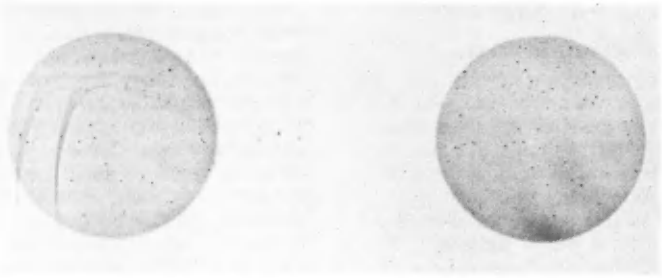


Fig. 4.—X-radiographs of a beryllium disc showing dust inclusions. This pair may be viewed stereoscopically.

CRACKS.

The detection of cracks by radiography, or indeed by any method, is a very intricate subject. It is obvious that when a crack appears in any object, there is no change in thickness of the material as viewed in a direction perpendicular to the plane of the crack. There is therefore nothing to show on a radiograph. When the direction of view is along the plane of a crack there is certainly a change in thickness of the material in the path of the radiation, but even then it is necessary for the width of the crack to be of sufficient magnitude to be resolved before it can be detected. It is possible for the path of the radiation to be almost in the plane of a crack and still no indication will be obtained. The deviation of path which can be tolerated will vary according to the width or separation of the crack. In practice it is found that a crack usually meanders and parts of it at least can be seen. Although taking a large number of radiographs from different angles, when a crack is suspected, may be tedious, this procedure can go a long way towards lessening the chances of any crack going undetected. It is, however, necessary to emphasise that absence of any indication of a crack on a radiograph can never be taken as conclusive evidence that a crack does not exist.

FILMS.

A range of special X-ray sensitive films is available to suit various requirements, covering several grades of contrast, emulsion grain size and exposure speeds, and the type most suitable for a particular subject is determined by experience. Intensifying screens and filters also play a part in keeping exposure times within reasonable limits and controlling scattered radiation from large irregularly shaped subjects.

SETTING UP PROCEDURE.

In setting up a subject for an X-ray photograph a number of factors have to be considered. A sheet of the correct type of film is selected and enclosed in a film holder or "cassette", sometimes with intensifying screens of appropriate characteristics. For a thin subject the aluminium wall of the film cassette may be too dense to allow sufficient contrast in the radiograph and it will be necessary to wrap the film in light-proof paper only. The subject is then laid on the film cassette on a table beneath the X-ray tube and set in correct alignment with the tube in order to give the required direction of view. Metre rules, spirit levels, plumb bobs and spot-lights, all play a part in this procedure. If the subject is one which must be maintained in a vertical position, for example, an open container of liquid, then the film cassette is held on a vertical rack and the X-ray beam is directed horizontally.

It may be necessary to mask off parts of the film or the subject with lead sheets in order to prevent over-exposure of the less dense sections

and consequent chemical fogging in the final radiograph. The tube voltage, current, choice of filter and exposure time are all interdependent and must be decided for each exposure. It may be necessary to take two or more views of a subject in different directions and, where practicable, this is usually done for convenience on the same sheet of film when all but the section being exposed at one time is masked off from the X-ray beam by lead sheets.

It is most important, to avoid possible confusion later, that each radiograph should have identification marks, and these, in the form of lead letters and figures, are usually attached to the film holder before the exposure is made. Location markers may also be desirable on the subject itself.

The processing of the films after exposure follows standard photographic practice.

INTERPRETATION OF RESULTS.

The interpretation of radiographs needs to be a co-operative effort between radiologist and "customer". The former must be able to contribute knowledge of such factors as the relative effects of different materials, the influence of the conditions under which the radiographs are taken on the information which they reveal, and the unfamiliar appearance assumed by three dimensional shapes when projected on to a plane film by a diverging beam of rays. The latter must know the characteristics of his product, the dimensions, and the possible defects which might arise. He also must take the final responsibility for deciding whether a defect when demonstrated to him is of sufficient magnitude to warrant the rejection of the article.

Fig. 5.—An isotope container made by Solus-Schall, Ltd., from G.E.C. Heavy Alloy.

In order to enhance the appearance of certain looked-for characteristics of an article, special techniques may be introduced. For example, a cooling tube embedded in a casting may be shown up much more clearly if filled with a comparatively opaque liquid, such as mercury; this follows a well-known medical practice. The change in position of a vacuum tube filament on heating may be demonstrated more readily by connecting it to a power supply and making the exposure half with the filament cold and half with it heated to normal operating temperature; the radiograph will then show two filaments, one in the position corresponding to the cold state, and the other in that corresponding to the hot state, which can be directly compared.

STEREOSCOPY.

It often happens that the need arises to determine the exact position of a feature within a subject which has been or is to be radiographed. Since a radiograph is essentially a shadowgraph, no particular plane of the subject is accentuated —although this can be done with elaborate equipment—and therefore no indication is given of the location parallel to the direction of view of any particular feature within the subject of examination. In order to obtain a fixation it is necessary to take a second radiograph with the subject in the same position and the X-ray tube moved through a short distance, and to observe the apparent shift of the feature of interest on the resulting radiograph with respect to locating markers attached to the surfaces. This produces in effect a stereoscopic pair which, if the tube shift was the appropriate distance, can be viewed using a suitable stereoscope and the position of the feature of interest can be seen directly.

Fig. 4 is a stereoscopic pair of radiographs of a beryllium disc such as is used for windows in some X-ray tubes. These discs are regularly examined before use in order to certify that they are free from dense inclusions. In the case illustrated, inclusions are present which appear to be dust particles of some substance heavier than beryllium. The stereoscopic presentation demonstrates that these are distributed throughout the thickness of the disc. If it is possible to view these reproductions one with each eye independently the superimposed discs will appear in three-dimensional form.

GAMMA-RADIOGRAPHY.

Until 1946 the only radioactive material generally available for gamma-radiography was radium. This, while of considerable value because of its uniqueness, and also its portability and compactness when compared with 1 million volt X-ray apparatus, nevertheless had several disadvantages, in particular high cost and large size necessary to give an effective radiograph in a reasonable time. Since 1946 several artificially produced radioactive materials have become available, the most notable being cobalt^{60}, tantalum^{182} and iridium^{192}. It has also become practicable to make use of the radioactive gas radon.

The cobalt and tantalum isotopes have similar radiation characteristics, quite comparable with radium, but are obtainable in much greater strengths. Useful radiographs can be obtained in a few hours with medium thick subjects or in about twenty-four hours with subjects of thickness comparable with 4 ins. of steel.

Iridium^{192} is perhaps the most versatile. Its radiation is less penetrating than the others, being equivalent to about 400 kV X-rays, but for many subjects this is an asset as greater contrast is obtained in the radiographs. Its main advantage is its great specific strength which enables very small sources to be produced. A strength of 1 curie can be obtained in a 2 millimetre cube and even smaller sources can be obtained for use in situations where the source-to-subject distance may be only a few inches. An example of such an application is the examination of welded joins in pipes. A radiograph of a weld over the whole circumference of a pipe can be obtained on one sheet of film, by wrapping the film around the outside of the pipe to cover the weld and inserting a very small radioactive source, carried on the end of a rod, down the middle of the pipe.

Gamma-ray sources must be kept in lead or Heavy Alloy containers specially designed for storage and exposure without handling. These containers usually weigh about 60 pounds, and are easily transportable (fig. 5). The usual practice in making an exposure is to set up the object in a place specially set apart for the work and to leave it overnight or for the required number of hours until the exposure is complete (figs. 6 and 7).

Safety precautions against the danger to health of excess exposure to the radiations are very necessary but can be easily organised.

RESEARCH AND DEVELOPMENT APPLICATIONS.

The subjects of examination met at the G.E.C. Research Laboratories cover a very wide field and work is carried out at one stage or another on nearly all the various articles in development or under investigation. The largest section is that of vacuum tubes and associated components, including thermionic valves of many kinds, cathode ray tubes, lamps, gas-filled tubes and discharge tubes. Domestic and heating appliances, boiling plates, immersion heaters and refrigerators also demand considerable attention.

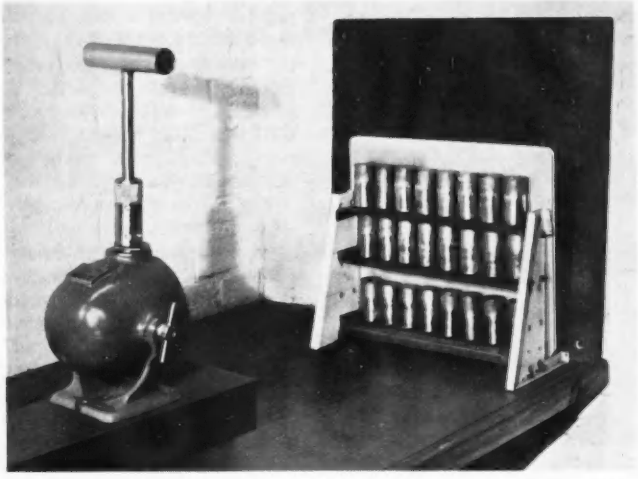


Fig. 6.—A batch of 24 heavy current circuit-breaker tips set up for gamma-radiography.

Many castings intended for laboratory apparatus or fabricated articles are regularly examined for internal defects, and a large number of unclassifiable miscellaneous items complete the list.

A special mention must be made of vacuum tubes. Most of these consist of a filament or cathode surrounded by a number of other metallic electrodes, the outer one in most cases being made of unperforated sheet, and the whole enclosed in a vacuum-tight envelope which is often opaque. As the proper functioning of these tubes depends on the various electrodes being correctly positioned, it is often essential in assessing the performance of an experimental sample to be quite sure that the electrodes really are in their correct position and undamaged. Although the greatest care may have been taken during assembly it is not always possible when glass working and heating processes are involved to be quite certain that the correct electrode positions have been maintained. It is therefore customary to radiograph many types at critical stages in their manufacture and processing in order to examine directly the electrode arrangement. An instance of this is given by the short wave types of transmitting valves which are usually of cylindrical construction and have very small clearances between the electrodes which may be as little as ·004 in. between cathode and grid. Until assembly jigs can be developed for a new type of valve

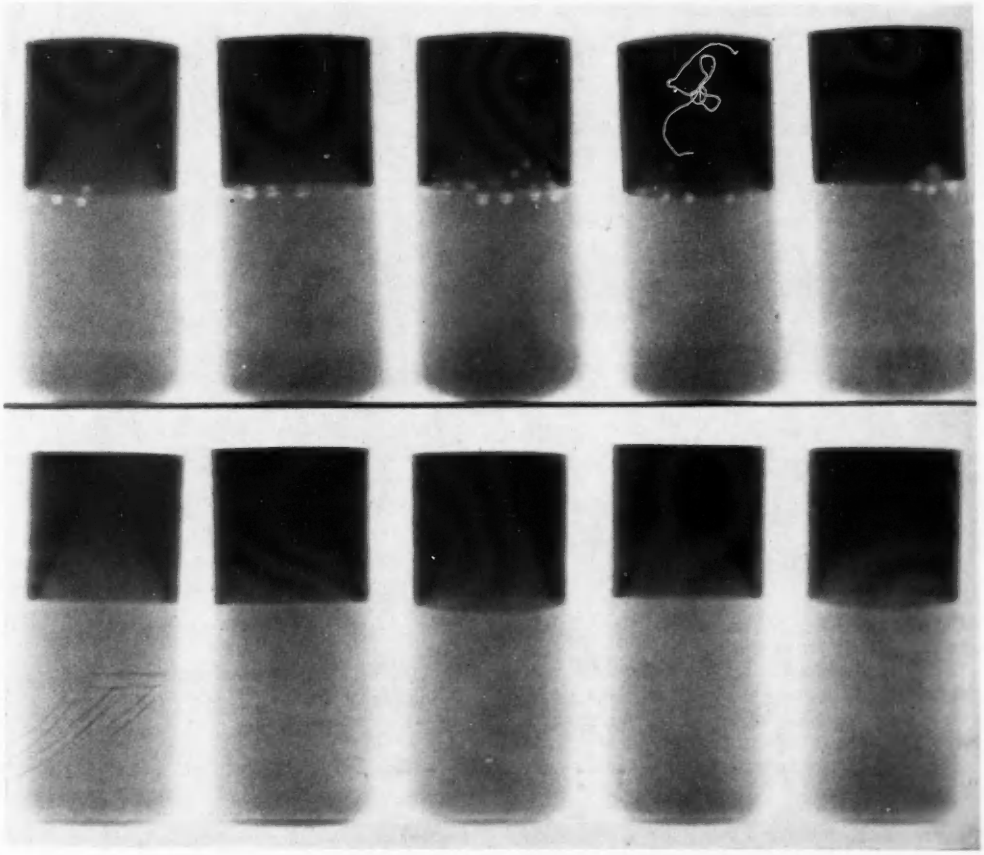


Fig. 7.—Gamma-radiograph of part of a batch of heavy current circuit-breaker tips showing several reject specimens with cavities at the junction of copper and Heavy Alloy.

which can ensure accurate assembly the radiographic examination is used to establish the actual condition of each sample.

Cylindrical assemblies as mentioned above present several distinctive difficulties. First, concentricity cannot be confirmed by a single radiograph unless it is an axial view, and this is not usually practicable due to confusion in the radiograph caused by the superimposition of seals, leads and connections, and also to the difficulty of obtaining true axial alignment. Two views, mutually perpendicular to the axis of symmetry, are usually recorded and are considered sufficient if the components are accurately shaped. Second, if one component of the electrode system is comparatively thick-walled, the clearance to the adjacent member inside it is not sharply defined because the projected thickness at this point is near the maximum and greatly in excess of the nominal thickness. This can be more readily appreciated by referring to fig. 8 which shows a section through the active electrode system of a CV2200 valve. Although the copper anode wall thickness is $\frac{1}{4}$ in. the maximum thickness of copper to be penetrated is greater than $\frac{3}{4}$ in. Plotting this projected thickness against the distance from the axis of symmetry demonstrates that the grid-to-cathode space at the diametrical extremes, which are the points of vital interest, is seen through almost the thickest part and where the thickness is changing rapidly.

Unless the wall thickness is very small in comparison with the diameter, the inside surface of any tube is far less easily delineated than the outside. The image sharpness does improve, however, if more penetrating radiation is used, and this is the solution adopted in the case of the CV2200 valve. Fig. 9 is a photograph of the valve with, for comparison, a radiograph made using an iridium^{192} gamma-ray source.

It occasionally becomes necessary to explore the variation in wall thickness of glass bulbs, as, for example, large cathode-ray tube bulbs. This might be done in some instances by direct measurement using callipers but would be very laborious and small irregularities would almost certainly be overlooked. The wall section can be demonstrated very effectively in a radiograph but here again, even in the case of soda (lead-free) glass bulbs, if the thickness is more than one or two millimetres fairly hard X-rays or gamma-rays are needed to produce the desired result.

Heating appliances, chiefly of the domestic type, frequently provide material for radiographic examinations. Most of these incorporate heater coils, embedded or enclosed in a metal tube or case. Individual specimens of these, which may be intended for performance trials, require to be checked in order to confirm that, at the time of test, the coils are in their correct positions, and so to ensure that measurements made will be truly representative of the product.

Again, an article subjected to a life test may burn out, and then it is often desirable to find

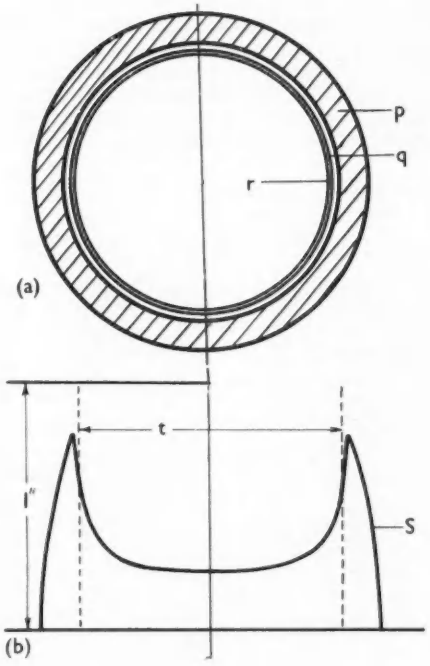


Fig. 8.—(**a**) Cross-section of working region of valve, type CV2200:
(*p*) Copper anode;
(*q*) plane of grid wires;
(*r*) plane of cathode surface.

(**b**) Projected section of parts shown:
(*s*) projected thickness of copper anode to be penetrated;
(*t*) limit position of grid wires.

the position and extent of the defect before the article is dismantled.

FLUOROSCOPY.

Certain light articles are often examined directly by projecting the X-ray image on to a fluorescent screen. The resolution is not nearly as good as that obtainable on a film, but where the internal features are sufficiently large and no permanent record is required the method ob-

viously gains on the score of rapidity. For example, in the use of polythene mouldings as insulators in high frequency radio circuits it is important that there should be no cavities or air bubbles in the moulded parts as these can upset the distribution of electrical energy in a circuit. Such cavities are readily detected by direct viewing.

Another item which lends itself admirably to fluoroscopic treatment is the replenisher capsule now being incorporated in some hydrogen-filled devices. These capsules are filled and sealed by an automatic machine, and, as a precaution, since only one capsule is used in each tube, batches are examined on the screen in order to make certain that each capsule contains the required quantity of active material.

CONCLUSION.

These examples should serve to illustrate the extensive variety of applications, in research work in the electrical field, in which radiography can be of valuable assistance. The precise location and diagnosis of faults, often impossible or uncertain by any other method, can clearly indicate the steps which should be taken to effect appropriate modifications or improvements in a product. By checking for freedom from faults or confirming the internal condition of an article, much time and expense can be saved, and confidence is established not only in the reliability of a product but also in the accuracy of representative performance figures and ratings which may be quoted for it.

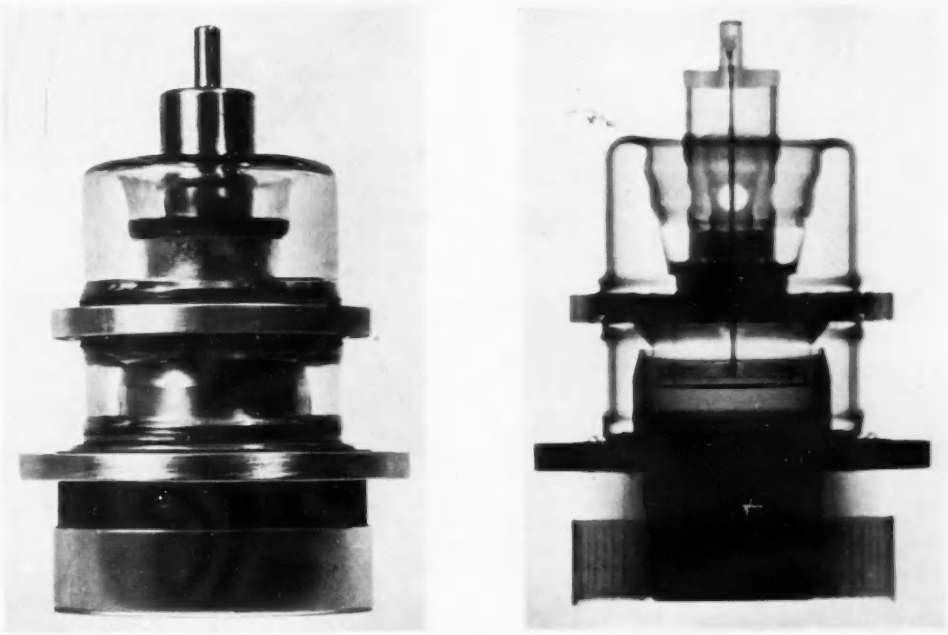


Fig. 9.—A photograph of a transmitting valve, type CV2200, with a gamma-radiograph for comparison.

A New Method for the Quantity Production of Glass Bulbs

Fig. 1.—The Works of Glass Bulbs, Ltd., at Harworth, near Doncaster.

INTRODUCTORY.

GLASS bulbs of a great many different types and sizes are required in vast quantities by the lamp and valve industries. Up to twenty-five years ago they were all made by skilled hand blowers, but since that time various automatic machines have been in use which are capable of producing bulbs in considerable quantities. However, the increasing demand both from home and overseas markets has made it necessary to undertake production on a scale never previously contemplated. Accordingly The British Thomson-Houston Co., Ltd., and The General Electric Co. Ltd., have jointly formed a new company, Glass Bulbs, Ltd., with a factory at Harworth, near Doncaster, Yorkshire (fig. 1), which is capable of producing one-and-a-half million glass bulbs a day. Production of all the bulbs required for Mazda and Osram general lighting service lamps is being concentrated at this factory ; in addition to this, the output is sufficient to meet the requirements of all other lamp manufacturers in the British Isles and to allow an ample margin for export to Europe and the Commonwealth. This vast production has been made possible by the installation of two ribbon-type machines which are the only ones of their kind outside the United States.

THE FACTORY.

The site of the factory at Harworth was carefully chosen so as to afford the special facilities required. Female labour is readily available in the nearby villages and an ample supply of coke oven gas, needed for firing the glass furnace, is obtainable from the adjacent Harworth Colliery. The factory building is 700 ft. long by 80 ft. wide and is laid out and equipped so as to take full advantage of the capacity of the ribbon

Fig. 2.—The mixing tower: suction pipes convey raw materials from rail trucks to the top of the silos.

machines. There are over 600 employees. The plant comprises the main factory building housing the furnace, ribbon machines, annealing lehrs, inspection point, packaging lines, chemical laboratory, stores, workshop and main offices. At one end is the 100 ft. mixing tower where the raw materials are taken in, and it is from this point that the manufacturing process begins, terminating in the finished products which, packed in cartons, are transferred on a conveyor belt to the finished bulb stores where they are loaded directly into railway wagons in which they travel to their destinations in this country or to the ports for shipment abroad.

MANUFACTURE.

The entire scheme of manufacture is based on a system of flow production and is highly mechanised throughout.

Private sidings on the factory site, which connect with a nearby railway line, enable the raw materials to be delivered directly to the works without transhipment.

From this point all of them are raised by suction to the top of the mixing tower, with the exception of the sand which is blown up under pressure (fig. 2).

The Mixing Tower.

This tower, which is built in reinforced concrete and rises to a height of 100 ft., merits a rather more detailed description. It is the only one of its kind at any glass works and presented some unique problems in structural engineering. It consists essentially of seven silos, extending from the top to the bottom of the tower, each of which is capable of holding 1,500 tons. The raw materials consist of soda ash, dolomites, limestone, sand and felspar in addition to cullet, or surplus glass, which is fed to its silo by a mechanical bucket conveyor inside the building. It is worth noting that all these materials are obtained in this country: the sand from King's Lynn in Norfolk, the soda ash from Northwich in Cheshire, the limestone from Buxton in Derbyshire and the dolomite

Fig. 3.—Mixing tower: weighing machines for the various ingredients.

Fig. 4.—Blender, or mixing drum, from which materials are discharged into canisters for conveyance to the furnace.

locally from a source near Doncaster. The resultant glass contains very roughly 72 per cent silica, 18 per cent soda, 6 per cent lime and 3 per cent magnesia.

The raw materials are reclaimed mechanically from shelves at the top of their respective silos and pass down chutes to the automatic weighing machines two floors below (fig. 3) whence they are discharged in their correct proportions into a rotary mixing drum.

On the floor directly below the outflow at the top of the tower are situated the remote control panels which give an accurate and instantaneous picture of the progress of events. Coloured indicator lights show the conditions in the silos, when they are being replenished, the passage of materials into the weighing machines, their discharge into the mixing drum and so forth. Most of these operations are remotely controlled by push buttons on the panels, so that a small staff of two men is able to supervise the working of this important section.

From the mixing drum the now thoroughly blended materials are automatically discharged into canisters which are mechanically conveyed on a roller runway to the hopper from which the furnace is fed (fig. 4). The hopper discharges into the electrically operated, mobile screw feeders which force the charge, or batch, into the mouth of the furnace.

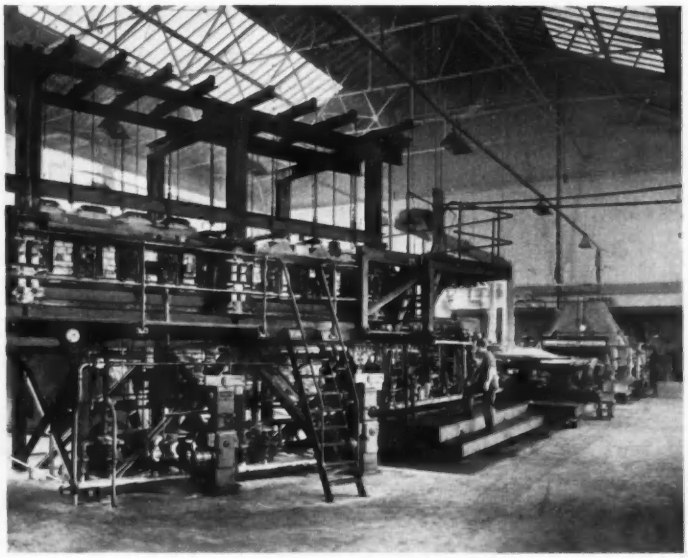


Fig. 5.—Forehearth and ribbon machine.

THE FURNACE.

This is a continuous tank type cross-fired regenerative furnace capable of producing 150 tons of glass a day. The furnace is fired with coke oven gas and the regenerative feature enables the incoming air to be pre-heated before entering the furnace, thus effecting a valuable economy in the use of fuel.

Temperatures are suitably graded through the melting and refining ends, the glass finally passing through the forehearths, which are of the most modern automatic type, and which bring the glass to the exact temperature required for feeding to the ribbon machines (fig. 5). Pressure in the furnace is maintained automatically at slightly above atmosphere. Remote recording and metering instruments are grouped on panels in the machine room.

THE RIBBON MACHINE.

On leaving the forehearth a controlled stream of glowing, molten glass flows down between two rotating water cooled rollers at one end of the ribbon machine (fig. 6). One roller has a plain surface, the other contains pockets, or circular depressions, so that the glass issues from between them as a continuous ribbon bearing a series of shallow circular protuberances or " humps " in appearance resembling the ribbon of " caps " used in a boy's toy pistol. On leaving the rollers the ribbon is carried on a continuous belt of orifice plates, each of which is pierced with a circular hole that comes accurately into position beneath a " hump." Moving forward on the orifice plates the ribbon now meets a continuous chain of blowheads which descend on to it from above, each blowhead pressing into the centre of a " hump " directly over a hole in each orifice plate.

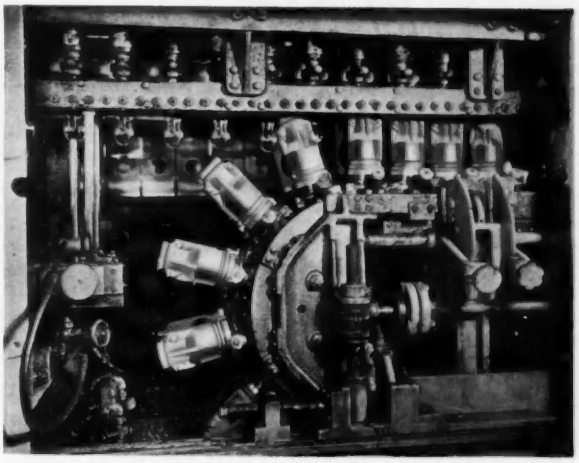


Fig. 7.—Glass blanks hanging from the ribbon meeting and entering the moulds.

Fig. 6.—The stream of molten glass from the furnace passing between the rollers that form the ribbon.

A puff of compressed air issuing from the blowhead causes the " hump " to be extruded downwards through the hole in the orifice plate, the function of which is to determine the diameter of the flare at the top of the neck of the finished bulb. These embryonic bulbs, or glass blanks as they are called, hanging below the rapidly moving ribbon, increase in depth until they meet the split moulds which rise from below on a continuous belt and close round them from both sides (fig. 7). The moulds now begin to rotate and meanwhile the air pressure from the blowheads increases so that the glass blanks are moulded to their final shape. It will be understood that during this operation the ribbon, blowheads and moulds are all moving forward together at the same speed. On completion of this pro-

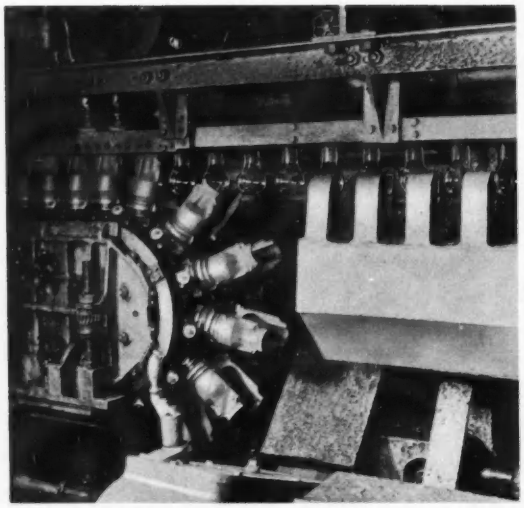


Fig. 8.—Finished bulbs leaving the moulds. Jets of cooling air are seen on the right.

cess the moulds open, revealing the bulbs (fig 8) and return on their belt under the machine. Similarly the blowheads break contact with the glass ribbon and return along the machine on the upper side of their chain. The orifice plates, carrying the ribbon with the blown bulbs depending from beneath it, continue to travel forwards while jets of cooling air play upon the completed bulbs. On reaching the rotating ribbon lifter the bulbs are successively tapped off by the strokes of a synchronised hammer and fall into the scoops of a rotary turntable which tip them on to a moving belt for conveyance through a gas-fired lehr, or annealing oven (fig. 9). The glass ribbon passes down to the floor below where it is watercooled and subsequently broken up for re-use as cullet, while the orifice plates return horizontally behind the machine.

While it is obviously not possible to describe these intricate machines in detail, the diagram in fig. 10 gives a clear picture of the complete process of bulb blowing. A few further facts may also prove of interest.

The moulding of the bulbs is essentially a very delicate and precise operation and for this reason the moulds are cork lined. The heat of the glass transforms the cork into fine carbon which readily absorbs water from the cooling sprays that play on the moulds as they pass back under the machine. Coming into contact with the hot glass, the water is vaporised,

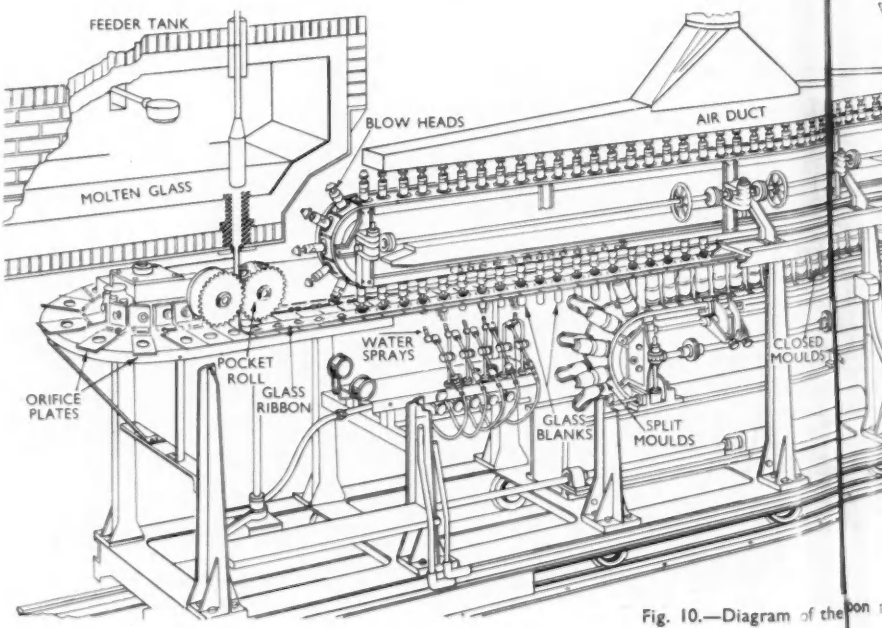


Fig. 10.—Diagram of the

so that the bulbs are formed in a cushion of steam which leaves them with a polished surface finish.

The two ribbon machines are of different sizes : the larger one has a pitch of 3·9 ins. from centre to centre of the orifice plates, the smaller a pitch of 3 ins. The pitch dimension naturally determines the size of bulb which can be blown. There are, in all, seven different sizes of orifice plate, and rollers of two different depths of pocket : $\frac{7}{32}$ in. and $\frac{9}{32}$ in. respectively. These adequately cover all the sizes of bulbs and valve envelopes produced.

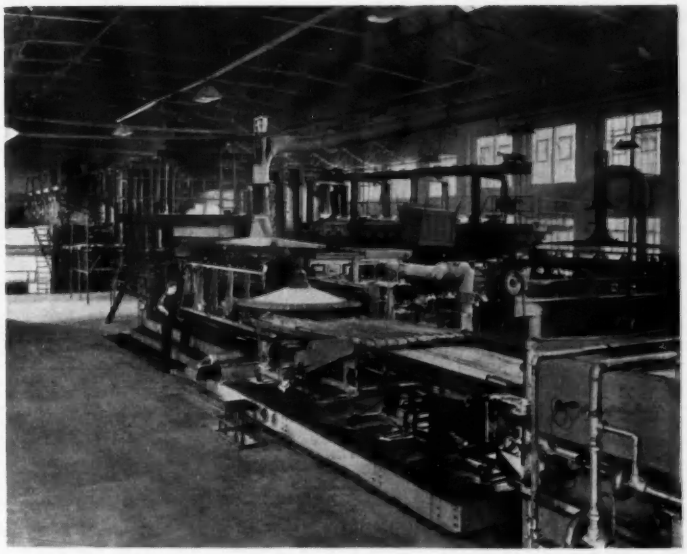
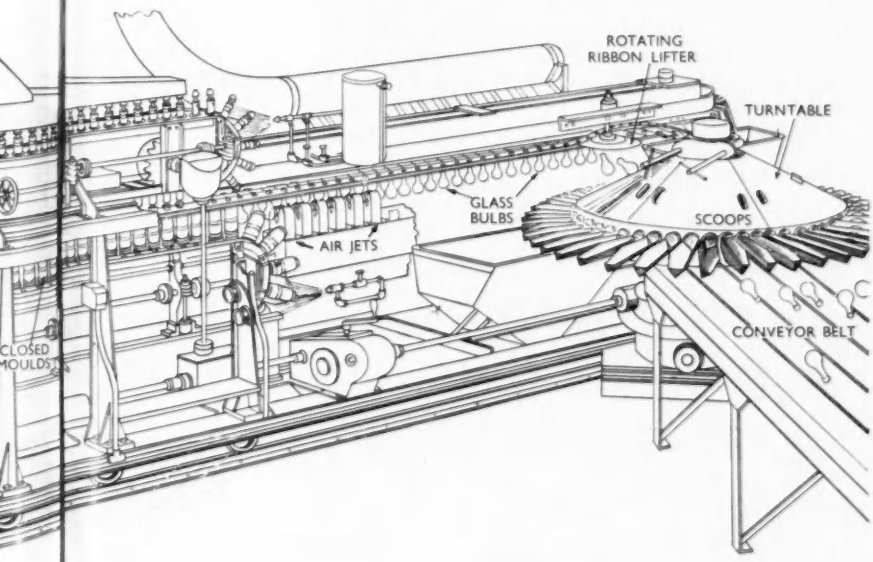


Fig. 9.—The furnace, ribbon machine and entry to the annealing oven.

An important characteristic of the ribbon machine is that it is much more versatile than any other bulb blowing machine. It will blow the miniature type of valve bulb at a very high speed and can be quickly turned over to the production of large size filament lamp bulbs. A further important feature is the consistency of the product and its constant



n of the bon machine in operation.

dimensional accuracy which greatly exceeds that previously obtainable from any other machine.

Each ribbon machine is driven by a 10 h.p. compound wound D.C. motor supplied from a 3-phase full-wave rectifier and operated under electronic control so arranged as to maintain constant speed at any setting within $\pm \frac{1}{2}$ of 1 per cent for a 10 per cent variation in voltage. This form of control enables the motor speed to be varied from a crawl to 1,750 r.p.m.

THE PRODUCT.

The larger machine, with moulds at 3·9 in. centres, produces from 350 to 500 bulbs a minute in the 70 mm., 75 mm., and 80 mm. sizes for 75 watt, 100 watt and 150 watt general lighting service lamps. Operating on a continuous 24 hour schedule, this machine gives a daily output of approximately 500,000 bulbs. The smaller machine, in which the mould centres are at a 3 in. pitch, will produce the whole range of valve bulbs up to 44·5 mm. diameter, including all the miniature types, and lamp bulbs from the 25 mm. stop and tail light size up to and including the 65 mm. bulb for the 60 watt general service lamp. The output of this machine, which runs continuously throughout the 24 hours, is approximately 1,000,000 bulbs daily.

INSPECTION.

After annealing, the bulbs are air-cooled while proceeding on a conveyor belt to the packers. At the control point five bulbs are picked off the belt every twelve minutes for examination and dimensional checks, continuous inspection being carried out on a quality control basis.

PACKING AND STORING.

The packing of bulbs into cartons, labelling and sealing down take place on two floors of the main factory building, whence the cartons pass on conveyors to the finished bulb store. This building is 700 ft. long by 110 ft. wide ; a railway line enters at one end and extends down one side for the full length of the store. On the opposite side are situated the road loading docks which are conveniently arranged at an angle to allow ample room for backing and turning the lorries. It is to be noted that all loading into road and rail vehicles takes place under cover.

Inside the store, cartons ready for despatch are stacked on palletts and can be easily picked up and transported by means of battery-driven fork trucks. Between twenty and thirty wagon loads of bulbs are despatched from the works by rail every day.

POWER SUPPLIES.

Electric power for the works is supplied from a transformer substation on the factory site. All the equipment is operated by A.C. motors with the exception of the ribbon machines which are driven by D.C. machines for which a rectified D.C. supply is provided.

As the manufacture of bulbs is a continuous process, and any interruption would involve wasteful and costly delay, arrangements have been made to ensure continuity of supply, in the event of a power cut, by the installation of emergency diesel-alternator sets. Similarly, oil storage tanks have been provided to enable the furnace to be oil-fired should the normal supply of gas fail.